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ALTERNATIVE FUELS FOR GAS TURBINES: A CONSEQUENTIAL LCA FOR ELECTRICITY GENERATION IN 2020

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DÉPARTEMENT DE GÉNIE CHIMIQUE

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présenté par : SURVEYER Alyson

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a été dûment accepté par le jury d'examen constitué de :

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DEDICATION

To my mother, for her life-long devotion to the education and happiness of her daughters.

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RÉSUMÉ

Ce projet de maîtrise porte sur une analyse de cycle de vie (ACV) de différents carburants alternatifs, dans diverses régions géographiques, produites dans le but de générer de l'électricité à travers une turbine à gaz en 2020. En effet, à ce temps, la technologie de turbines du partenaire industriel aura l'aptitude de brûler ces différents types de carburants de façon efficace. Conséquemment, l'objectif principal de cette étude est d'identifier où et avec quel(s) carburant(s) alternatif(s), une turbine à gaz devrait être opéré considérant ses impacts environnementaux et la faisabilité du marché ainsi que les lignes directrices du partenaire industriel.

Afin de répondre à l'objectif principal, la première tâche à entreprendre est celle de déterminer le contexte géographique de l'étude ainsi que les matières premières ayant le plus de potentiel pour un approvisionnement futur et assurant une faisabilité technique. Afin de faire ceci, une revue de littérature fût entreprise sur les potentiels bioénergétiques des années futures et les facteurs récurrents et significatifs ont été pris en compte dans l'étude de marché entreprise dans ce projet (Smeets et al., 2007). Ils se listent comme; les politiques nationales sur la bioénergie dans les pays étudiés, l'approvisionnement et la disponibilité des matières premières, l'état de l'avancement technologique et la production actuelle et projetée de carburants alternatifs ainsi que leur coûts de production en 2020. Après cette analyse de marché, les scénarios suivants ont été identifiés comme ayant un bon potentiel : syngaz provenant de résidus forestiers et biogaz issue d'engrais animal en Allemagne, biogaz dérivant de déchets solides municipaux en Italie, biodiesel provenant d'huile de palme en Indonésie, bioéthanol issue de la canne à sucre au Brésil, syngaz résultant de la gazéification du charbon en Chine et aux États-Unis ainsi que le biodiesel provenant de suif animal, et l'éthanol de résidus de maïs aux États-Unis.

Les deuxième et troisième objectifs étaient respectivement de; 1- identifier quels carburants alternatifs avaient de potentiel impacts environnementaux les plus faibles considérant leurs différentes matières premières et leur contexte géographique et, 2- identifier où se situe le plus grand bénéfice de l'utilisation de ces carburants pour la génération d'électricité, considérant la substitution de celle-ci à sa source d'énergie compétitrice dans les régions étudiées. Ces deux objectifs sont répondus en conduisant une analyse de cycle de vie conséquentielle (ACV-C) et prospective sur les scénarios déterminés précédemment.

L'ACV-C conduite prend en compte différents éléments tels que l'extension des frontières pour les procédés à multiples coproduits, les impacts indirects de l'utilisation de matières premières contraintes, les changements indirects de l'utilisation des terres et les impacts liés à la substitution d'électricité.

Afin d'implanter correctement l'extension des frontières, l'approche de Weidema (2003) a été utilisée. Cet aspect est important puisqu'il n'y a aucun consensus sur la méthodologie à appliquer. Dans le cas où des répercussions indirectes résultantes de la production de cultures énergétiques peuvent se manifester sur d'autres cultures liées sur le marché agricole, l'approche de Schmidt et Weidema (2008) qui a été préférée. Celle-ci permet d'identifier l'état d'équilibre des incidences du marché et calculer les quantités de cultures énergétiques évités ou additionnelles.

Les effets indirects de l'utilisation de ressources contraintes ont été pris en compte puisque ces matériaux sont considérés comme ayant un approvisionnement inélastique et conséquemment, ne peuvent pas répondre à un changement de demande. Essentiellement, s'il y avait une utilisation de ses matières premières pour d'autres applications, leur disponibilité seraient réduite pour les utilisateurs courants (ou les systèmes de gestion de déchets) et ces impacts devraient être modélisés.

D'autre part, il n'est possible de démentir que les études d'ACV portant sur les biocarburants doivent maintenant inclure des études sur les émissions provenant de l'utilisation indirecte des terres puisque celles-ci ont été prouvées comme étant significatives et pouvant possiblement inverser les conclusions d'ACV (Searchinger et al., 2008). La méthode utilisée est celle de causes à effets, se traduisant en une élaboration des façons d'atteindre une production additionnelle de biocarburants, dans différentes régions identifiées comme productrices marginales de cultures énergétiques impliquées (directement ou indirectement) dans le processus (Bauen et al., 2010).

Finalement, l'identification de sources marginales d'électricité pour chaque scénario est entreprise puisque l'opération de la turbine substitue une électricité générée par la centrale électrique marginale. Les approches à court terme et long terme ont été utilisées afin d'identifier respectivement le changement dans les centrales électriques installés et les futures investissements en capacités électriques. L'approche de Weidema (2003) fût encore une fois utilisée afin d'identifier la technologie affectée à long terme, cependant quelques ajustements à cette méthode ont été fait. En effet, considérer plusieurs technologies marginales et prendre en compte les caractéristiques des turbines, (e.g., la capacité de suivre la charge électrique) sont des aspects qui ont été ajouté à la méthode. De plus, l'approche à cour terme a été basée sur l'identification des technologies affectées à travers les coûts marginaux (i.e., les coûts de carburants) (Amor et al., 2011). En effet, les centrales qui partagent les mêmes coûts marginaux que celle de la turbine utilisant les carburants alternatifs respectifs, sont identifiés comme étant les technologies affectées.

Les résultats de l'étude ACV-C démontrent que les tendances les plus dominantes sont que le syngaz provenant du charbon aux États-Unis et en Chine sont les scénarios les pires d'un point de vue environnemental, suivi, de très près, de l'éthanol Brésilien et l'éthanol Américain. D'autre part, les scénarios les plus prometteurs varient selon la catégorie d'impacts étudiés, cependant le biodiesel Indonésien – à l'exception des dommages sur la qualité des écosystèmes-suivi du syngaz et biogaz Allemand sont toujours dans les scénarios les plus performants du point de vue environnemental. Les scénarios restants varient aussi considérablement dans leur performance selon le type d'impact analysé, conséquemment il reste donc aux soins du partenaire de valoriser une catégorie d'impact au détriment d'une autre selon son système de valeur.

Finalement, plusieurs analyses de sensibilités ont été réalisées afin de vérifier certaines hypothèses portant sur la production des carburants, l'opération des turbines, la méthode de caractérisation des impacts et la substitution d'électricité. L'intérêt de faire ces analyses est de vérifier si certaines hypothèses peuvent inverser les conclusions des études. Par exemple, pour plusieurs hypothèses reliées à la production des carburants, les conclusions étaient renversées, spécialement dans le cas du changement climatique et l'épuisement des ressources. Le changement le plus significatif dans les résultats est celui de la diversion du suif animal pour différentes applications du marché. Également, les impacts résultant de l'identification de différentes centrales électriques affectées, sont significatifs et changent en bonne partie l'ordre de classement des scénarios, cependant les tendances mentionnées précédemment sont toujours maintenues. En conclusion, l'étude permet au partenaire industriel de; positionner ses priorités en termes de recherches subséquentes sur les carburants alternatifs, perfectionner leur planification stratégique dans leur développement d'affaire et possiblement utilisée celle-ci comme outil de marketing envers leurs clients et le public.

ABSTRACT

This master's project focuses on a LCA assessment of alternative fuels in disperse geographical locations for electricity generation through a gas turbine in 2020. Indeed, by then, the industrial partner's gas turbine technology should have the ability to burn these different fuels efficiently. The study's main objective is therefore to determine the location and alternative fuel types that should be used to operate the gas turbine, considering environmental impacts and market feasibility and according to the industrial partner's guidelines.

In order to achieve the main objective, the first task was to determine the geographical context and feedstock with the most potential for future supply and technical feasibility based on the alternative fuels and industrial partner's guidelines. The literature on the bioenergy market was therefore assessed, and several recurring important factors were taken into account, including the bioenergy policies in the assessed regions, feedstock supply and availability, the state of the art and current and projected fuel production volumes and costs (Smeets et al., 2007). In the end, the following scenarios were found to have future potential supply: syngas from forest residues and biogas from manure in Germany, biogas from MSW in Italy, biodiesel from palm oil in Indonesia, bioethanol from sugarcane in Brazil, syngas from coal, biodiesel from tallow, bioethanol from corn stover in the US and finally syngas from coal in China.

The second and third objectives were respectively to identify the alternative fuels with less overall potential environmental impacts considering their different feedstocks and geographical contexts and determine the locations where there is a greater potential benefit from the use of these fuels for electricity generation as compared to the competing source of electricity in the relative countries. Both objectives were answered by conducting a prospective consequential life cycle assessment (CLCA) on the scenarios determined by the first objective.

The CLCA methodology takes many different aspects into account, including system expansion for co-producing processes, indirect impacts from the use of constrained feedstock, indirect land use change (LUC) from energy crop cultivation and the impacts of electricity substitution.
Weidema's (2003) approach was used to correctly implement the system expansion, which is an important issue, since there is no consensus on the applied methodology. When a knock-on (i.e.

incidental) effect from crop production was shown on other market-linked energy crops, Schmidt and Weidema's (2008) approach was chosen to find the equilibrium state and calculate the avoided or additional crop production. Indirect impacts from the use of constrained resources were taken into account, since the materials were considered to have inelastic supply and thus could not respond to a change in demand.

Essentially, should these sources of biomass be used for alternate applications, their availability would be reduced for the current users or waste systems. Hence, indirect impacts linked to the former must be modeled. On the other hand, there is no denying that LCA studies on potential biofuel impacts now require assessments of ILUC impacts, which have been proven to be significant and could invert certain study conclusions (Searchinger et al., 2008). The causal-descriptive method, which maps out the ways additional biofuel production could be attained in various regions identified as marginal producers, was used (Bauen et al, 2010).

Finally, the marginal source of electricity in each scenario was determined, since the substitution of the electricity by the alternative fuels had to be assessed. The short-term and long-term approaches were used to evaluate the changes in installed power plants and future capacity investments, respectively. Weidema's approach (2008) was again used to assess the long-term affected technologies, and the method was adjusted. Indeed, in some cases, more than one technology was identified and the load following ability of the energy sources was taken into account in the identification process. Otherwise, the short-term approach was used and based on determining the affected technology through its marginal costs (i.e. fuel costs), and the technologies that shared the same marginal costs as the turbine running on its respective alternative fuel was identified as the affected technology.

Based on the results, the most dominant trends are that syngas from coal in the US and China have the worst environmental performance in all endpoint categories, followed closely by ethanol in Brazil and ethanol in the US. On the other hand, the most promising scenarios vary depending on the impact category taken into account. However, POME in Indonesia – with the exeption of ecosystem quality- followed by syngas and biogas in Germany are always among the highest ranking options in terms of environmental performance. The remaining scenarios also vary considerably in their scores depending on the type of impact. Consequently, it is the industrial partner's responsibility to value one impact category over another according to its own standards.

Several sensitivity analyses were performed in order to verify fuel production, gas turbine operation, the impact characterization method and the electricity substitution assumptions in order to verify whether certain hypotheses invert some of the study's conclusions. For instance, many fuel production assumptions reversed the conclusions, especially for the climate change and resource depletion endpoint categories. The most significant changes arose from the deviation of tallow to the different market applications and are noted for every category of impact. Additionally, the impacts resulting from the identification of different affected power plants are most significant and change the scenario ranking. However, the aforementioned trends remain unchanged. In conclusion, the study enables the partner to position its priorities in subsequent alternative fuel studies, perfect its strategic planning for business development and possibly use this study as a marketing tool for clients and the public.

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ACRONYMS AND ABBREVIATIONS

ALCA: Attributional life cycle assessment

BL: Barley

BR: Brazil

CC: Combined cycle

CC: Climate change

CHP: Combined heat and power

CLCA: Consequential life cycle assessment

CN: China

CO_2 eq: CO_2 equivalent

DALY: Disability-adjusted life years

DE: Germany

D-LCA: Dynamic life cycle assessment

EPD: Environmental product declaration

EQ: Ecosystem quality

EtOH: Ethanol

FU: Scandinavian fodder unit

GHG: Greenhouse gases

GT: Gas turbine

HH: Human health

HHV: Higher heating value

HTU: Hydrothermal upgrading

ID: Indonesia

ILUC: Indirect land use change

IPCC: Intergovernmental Panel on Climate Change

IT: Italy

IGCC: Integrated gasification combined cycle

kWh: Kilowatt hour

LCA: Life cycle assessment

LCI: Life cycle inventory

LUC: Land use change

M-LCA: Macroeconomic LCA

MJ: Megajoule

MSW: Municipal solid waste

MW: Megawatt

NG: Natural gas

Nm^3: Normal cubic meter

OECD: Organisation for Economic Co-operation and Development

O&M: Operation and maintenance

OFMSW: Organic fraction of municipal solid waste

PDF: Potentially disappeared fraction

PFB: Palm fruit bunches

PKE: Palm kernel expeller

PKO: Palm kernel meal

PO: Palm oil

POME: Palm oil methyl ester

RD: Resource depletion

SM: Soybean meal

TME: Tallow methyl ester

Mtoe: Mega ton of oil equivalent

UK: United Kingdom

US: United States

YAM: Yearly average marginal technology

APPENDICES

INTRODUCTION

General context and challenges

The global electricity demand is expected to double between 2002 and 2030. Additionally, the power sector is projected to account for almost 45% of global energy-related CO_2 emissions by 2030. By then, coal plants in developing countries alone will produce more CO_2 than the entire OECD power sector (IEA, 2004). It is therefore imperative to try to reduce the environmental impacts of electricity generation by diverting conventional electricity generation technologies to other types of energy sources in order to lower operating emissions. Indeed, the current global energy supply is dominated by fossil fuels, which account for approximately 500 EJ per year. On the other hand, biomass contributes approximately 50 EJ/yr, making it the most important renewable energy source by far. The increase in the use of biomass for bioenergy production (i.e. biofuel and biopower) in recent years is mainly due to the implementation of favourable international and national political frameworks. Currently, most of this biomass is used for traditional non-commercial uses and contributes approximately 6.4 EJ/yr to power generation and industrial applications (Dornburg et al., 2010).

On another note, the advantages of gas turbines for electricity generation applications are numerous, especially considering their high fuel efficiency and lower emissions per unit of output compared to conventional fossil fuel technologies. Moreover, they show great potential in operations with liquid and gaseous alternative fuels—a strategic advantage for conventional thermal plants considering the continued depletion of fossil resources leading to uncertain fuel supply and volatile costs and the potential to reduce greenhouse gas (GHG) emissions. These alternative fuels are mainly derived from biomass and even coal (in the case of syngas).

Biomass is mainly used to reduce GHG emissions. In order to correctly assess these emissions, the type of biomass used for energy, its related co-products, the land-use changes that occur, the indirect effects if the biomass comes from a constrained resource and the electricity source that is replaced by the use of biomass for energy must all be taken into account (Brander & Hutchison, 2009; Dornburg, et al., 2010). Indeed, using land for biomass from energy crops leads to land conversion and the loss of considerable carbon stocks in soils or above-ground biomass

(Searchinger et al., 2008). Life cycle assessment (LCA) can correctly assess these types of environmental impacts. There are two main types of LCA: attributional LCA (ALCA) and consequential LCA (CLCA). A CLCA must be carried out to adequately assess the complexity of the systems (caused by land use changes, the substitution of displaced electricity systems, co-producing systems, etc.), since CLCA accounts for indirect/marginal impacts that are not explicitly included in attributional analyses. Indeed, CLCA accounts for activities inside and outside the life cycle that are affected by an incremental change and thus provides a methodological framework capable of assessing the indirect impacts that are intrinsic to the systems at hand (U.S.EPA, 2009).

In addition, the locations of the gas turbines running on alternative fuels must be determined based on market demand, feedstock supply availability and technical feasibility. Consequently, this study must first identify viable scenarios that will become the object of the CLCA study.

Objectives

In light of its particular industrial applications, the study is driven by a series of objectives rather than a particular hypothesis. The study's main objective is to determine the location and alternative fuel type that should be used to operate a simple cycle gas turbine considering the environmental impacts and market feasibility. The first part of the study on the technical feasibility of turbine operation is guided by the objective to:

- Determine the geographical context and feedstock with most potential for future supply and technical feasibility according to the selected alternative fuels and industrial partner guidelines.

This objective leads to the second part of the study on the environmental considerations of the alternative fuels to:

- Identify the alternative fuels with fewer overall potential environmental impacts considering their feedstocks and geographical contexts;
- Determine the locations where there is a greater potential benefit from the use of these fuels for electricity generation as compared to the competing sources of electricity in the relative countries.

The first objective is attained by looking at how future bioenergy potential production is assessed in the literature and translating the approach as closely as possible for specific alternative fuels. The second and third objectives are answered simultaneously by carrying out a prospective consequential LCA of the different scenarios.

Content of the thesis

Chapter 1 is a literature review of the gas turbine context and applications as well as the production pathways of different alternative fuels. It describes the basics of LCA methodology and finally covers the specifics on the determination of the marginal technologies and indirect impacts due to land use changes and the use of constrained resources. Chapter 2 outlines the study methodology. Chapter 3 presents the results of the assessment of the potential supply of alternative fuels and regions considered in the study as well as the CLCA results Chapter 4 is a discussion on the general results and the results of the sensitivity analyses. Finally, the last sections highlight certain study limitations and set out recommendations.

CONTEXT

This study was conducted as a Mitacs research project as part of a wider effort by the Consortium for Research and Innovation in Aerospace in Québec (CRIAQ) to explore novel fuels for gas turbine applications. The collaborative efforts were tailored to a sponsoring industrial partner in the aerospace industry. The author also carried out an internship, mainly to collect study data. This project is the first of many undertaken by graduate students in different institutions as part of the same CRIAQ project.

The CRIAQ is an aerospace research consortium in Québec that aims to carry out collaborative research projects for the industry. It is a non-profit organization that is mandated and funded by businesses and universities. The CRIAQ has launched thematic research on green aviation, the environment, safety and icing. At the core of this theme is the *Exploration of novel fuels for gas turbine* project, which involves several researchers and universities. The research was piloted by an industry leader that is also supporting a series of on-going projects with the same objective. This study is the first of this series. While others are more technical and based on the combustion of novel fuels in the turbine (e.g. on flame properties during the combustion), this study aims to point other researchers toward preferable types of fuels from a life cycle perspective.

The Mitacs-Accelerate program, a research internship program that connects companies and universities through graduate student initiatives, also funded this project. Mitacs-Accelerate enables interns to transfer their skills and expertise to an industrial application, providing businesses with a competitive advantage. The main goal of the internship carried out by the author was study data collection. However, the author also had the opportunity to become more familiar with the aerospace industry, share her life cycle assessment (LCA) expertise, collaborate on an internal novel fuels workshop and develop knowledge in the energy sector. Most importantly, the author was able to determine the needs of the industrial partner in order to translate them into study objectives and guidelines.

CHAPTER 1 LITTERATURE REVIEW

To properly assess the scope of the project, the literature review must cover four topics: gas turbine characteristics and applications as well as specificities on their possible geographical location, future potential bioenergy supply assessments and general descriptions of alternative fuels and their production processes, LCA and its definitions, types, applications and general methodology, and, finally, the methodologies used to determine the affected technologies based on the study context. Figure 1-9 provides an overview of the literature review, and Figure 1-10 illustrates the sections and corresponding objectives.

Gas turbine and alternative fuels applications
(section 1.1)

General context of the study

- The partner's guidelines for the study
- Advantages of GTs for power generation
- Current uses of alternative fuels in GTs (technical feasibility of their combustion and current commercial power plants)
- Illustration of why GTs would most realistically be located in the country where the fuel is produced

Bioenergy and Alternative fuels
(section 1.2)

- Definition of bioenergy concepts
- Different approaches to asessing potential bioenergy supplies
- Description of the production processes for the different alternative fuels assessed

Life cycle assessment
(section 1.3)

- Definitions, applications and general methodology
- Definition of different types of LCA, indicating which types are best suited to this study

Affected technologies and methods of identification
(section 1.4)

- Grounds for the identification of affected technologies in CLCAs and description of a system expansion
- Different approaches to identifying the affected technologies (general, applied case for PO, macroeconomic)
- General concepts when handling products coming from constrained resources (applied cases)
- Definitions and methodologies pertaining to the calculations of LUC.
- Different approaches to the identification of long term affected electricity sources and their characteristics
- Different approaches to the identification of short term affected electricity sources and their characteristics

Figure 1-1: Overview of the literature review

1.1 Gas turbines and alternative fuel applications

In order to properly establish the purpose of this study, the characteristics of gas turbines and the trends in the alternative fuels used to power them had to be put into context. An important section on why the turbine should be located near the fuel source is presented in order to introduce the feedstock, fuel and region assessment methodology.

The industrial partner's guidelines

The project will be based on a medium size turbine (40 -70 MW) since it is considered best suited in the partner's portfolio for the combustion of alternative fuels. This is so because that power range is most appropriate for the power generation market as opposed to lower output turbines that are used for mechanical drive in oil and gas platforms. The model is generally operated on natural gas, but may run on diesel as well.

- The gas turbine should run on a **simple cycle**, because of the partner's willingness to explore their technology on a baseline scenario.
- The alternative fuels of interest are; **biogas, syngas, bio-ethanol** and **biodiesel**.
- The assessment of **syngas from coal** should be emphasized.
- The study accounts for the context in **2020**. By that time, it is anticipated that there will be sufficient production capacity of these alternative fuels to use them in turbines for power generation (Refer to Appendix IV).
- The study should aim to identify potential future markets demands in order to determine potential market and clients.

Finally, the project's business value for the partner was to guide its novel fuels research and back its future investments.

1.1.1 Gas turbine characteristics

The use of GTs in electricity generation is increasingly common and is expected to increase by 2.1%/year in the 2007–2035 projection period, mainly due to their advantageous characteristics as compared to other technologies and energy sources (see list below (US Department of Energy & Laboratory, 2007)

- Modular: GTs may be located close to the fuel source and/or close to the electricity demands, making them a very interesting type of prime mover for distributed electricity. This characteristic is also significant to the efforts to reduce electricity losses through long distribution networks and enhanced reliability.

- Operational flexibility: GTs start up and shut down easily and in a short time period, rendering them ideal for load following.
- Smaller infrastructures: The twofold advantage involves less project time and less capital investment.
- High efficiency: This is the case when compared to steam turbines and especially when operated in combined cycles, in which GTs may reach 55 to 60% efficiency.
- Less maintenance: This is partly due to their simplified and smaller systems that provide easy access.
- Cost of electricity generation ($/kWh): GTs are competitive with other energy sources (e.g. coal, nuclear and wind) given their relatively low fixed costs, if fuel prices are low (IEA, 2004), as illustrated in Table 1.1. However, GTs are much more sensitive to fuel prices than many other technologies.

In this particular study, the most important characteristic of GTs is their fuel flexibility (i.e. ability to burn different liquid and gaseous fuels.)

Table 1.1: Levelized electricity costs of new generating technologies in 2016 (2009 USD/MWh) (EIA, 2011b)

Plant type	Levelized capital cost	Fixed O&M costs	Variable O&M (including fuel)	Total system levelized cost
Conventional coal	65.3	3.9	24.3	94.8
Advanced coal	74.6	7.9	25.7	109.4
Conventional natural gas (CC)	17.5	1.9	45.6	66.1
Advanced natural	17.9	1.9	42.1	63.1

gas (CC)				
Advanced nuclear	90.1	11.1	11.7	113.9
Wind	83.9	9.6	0	97
Hydro	74.5	3.8	6.3	86.4

1.1.2 Alternative fuels and gas turbines

The objective of this section is to demonstrate that the turbines should be located in the region where the fuel is produced. This would eventually underline the need to evaluate turbine locations based on fuel and feedstock types, which remains a key factor in this study and will be assessed in the methodology chapter.

1.1.2.1 Technical feasibility of the partner's technology with alternative fuels

The use of alternative fuels in gas turbines is in its earliest stages. The best evidence of this is the fact that gas turbines are not yet designed to burn alternative fuels. However, in the case of biodiesel, only minimal adjustments must be made (Rogriguez Coronado et al., 2009), and the partner has already tested with B10 (i.e., a blend of 10% biodiesel and 90% petrol diesel) blends (Johnson, 2011). Bioethanol is different in that there are some adjustments to be made in the engine, since ethanol has poor lubricity and is slightly corrosive. Also, the fuel auxiliary system must be adjusted to increase fuel flow due to the lower energy content of the ethanol (Moliere et al., 2009). Biogas should not involve too many adjustments, since its content is very similar to that of natural gas, except for the presence of high inerts in the fuel. The industrial collaborator has some experience in burning these types of fuels in its engine and can therefore manage the inerts (Johnson, 2011). However, biogas should first be compressed and then burned close to the source (otherwise transportation costs reduce the profitability) (Moliere, et al., 2009). The biggest challenge is syngas, mainly because of its very low energy content, which requires that significant amounts of fuel be fed into the turbines. In this particular case, the engine and the feed system must be modified (Lee et al., 2009; Gadde et al., 2006). Taking these factors into account, the partner affirmed that the integration of alternative fuels into gas turbine applications should not be expected earlier than 2020 (Johnson, 2011).

1.1.2.2 Commercial plants

GE and Petrobas have implemented the only commercial plant in the world to burn ethanol in gas turbines (as of 2010). Located in Juiz de Fora, Brazil, the plant runs on a simple cycle and has two gas turbines—one of which is equipped with a modified combustion chamber capable of burning both ethanol and natural gas. At least one commercial power plant running on bioethanol exists. However, the general trends of other alternative fuels being burned in power plants are quite different. In 2007, the final end product of 19% of all gasification plants was power. At the time, the worldwide gasification industry totalled 73 373 MWth and had different feedstocks such as biomass, petcoke, gas, petroleum and, most importantly, coal (US Department of Energy & Laboratory, 2007). The sizes of these plants are considerable, and a number of gasification-based power plant projects are planned in the US and China beyond 2010. Biogas, on the other hand, is often used in decentralized agricultural farms or landfills for heat and electricity generation, generally in engines, fuel cells, boilers and gas turbines for higher energy output (EurObser'ER, 2008). Like biogas, biodiesel is currently used for power generation in much smaller capacities (<5MW) to provide energy to residential buildings, hospitals or industries (plants).

1.1.3 Turbine location (geographical context of the study)

This section aims to confirm that the turbine should be located (i.e. installed and operated) where the fuel is produced. As previously stated, the geographical context of this case study is based on regions that hold promise for alternative fuel production to: 1) remain coherent with current international biofuel trading; 2) reduce transport; 3) secure the fuel supply and 4) ensure technical feasibility. The latter is especially relevant when transporting gaseous fuels over long distances, considering the possible lack of infrastructures and the development of integrated combined cycle power plants (IGCC).

1.1.3.1 Transportation and secure fuel supply

Reducing transport will lessen the overall environmental burden and, for some cases, reduce transport costs. As for securing the fuel supply, governments are certainly willing to invest in alternative fuels in order to be less dependent on imported fuel resources. It would therefore be important to assess locally-produced fuels in order to address the issue.

1.1.3.2 International biofuel trade

Europe has only recently implemented change, as Scandinavian countries have begun to trade certain types of biomass (pellets, wood chips, industrial by-products,etc.). However, the current trend remains that biofuels are usually produced and used locally (European Biomass Industry Association, 2006). The main issue in the trade industry is that there is no exchange regime applicable to biofuels and conditions vary greatly between countries. It is also a very complex system, since so many different products are involved (raw materials, by-products, biofuels) (Dufey, 2006). The other issues involve the fact that there is no specific category for biofuels in the trade system, the use of tariffs in some countries to protect agriculture and biofuel industries from foreign competition (taxes or customs duty), the use of quotas to regulate the biofuel exchange, domestic support (incentives) in industrialized countries, technological standards, etc. (Dufey, 2006). This is without counting the additional transport costs and relative environmental burden from international trade. Hence, gas turbines using local fuel resources may play a prominent role in the development of cleaner and more reliable energy efficient power systems.

1.2 Bioenergy and alternative fuels

This section introduces the four alternative fuels of interest for our partner and their multiple production processes and clarifies the relevance of the assessment of the potential biomass supply by describing methods to identify the potentials. Finally, the section illustrates what the alternative fuel production might involve (co-products, waste, generated heat and power etc.) to help determine why a particular production process was chosen over another.

1.2.1 Context and definition

Alternative fuels have shown great potential in the transport sector. In fact, some service stations in the US now also sell hydrogen, bioethanol, biodiesel, liquefied and compressed natural gas, etc. In recent years, the importance of these fuels has grown significantly for other applications such as power generation. Indeed, there is a need to green the grid mixes since the electricity sector is responsible for 23% of GHG emissions worldwide (IEA, 2010b). Many strategies have been set out to reduce these emissions: virtual power plants, power storage, cogeneration, bioenergy, carbon storage, improved efficiencies etc. Alternative fuels burned in gas turbines may address some of the issues by providing energy independence, greater efficiency and possibly lower GHG emissions. Table 1.2 differentiates and outlines definitions for certain key bioenergy terms.

Table 1.2: Bioenergy terms

Term	**Definition**
Conventional fuel	Includes fossil fuels (e.g. petroleum (oil), coal, propane, natural gas), nuclear (uranium), hydropower, etc. (Ecolife, 2011)
Alternative fuel	Any material or substance that can be used as fuel, other than conventional fuels (e.g. biodiesel, bio-alcohols, hydrogen, biomass, syngas, etc.) (Ecolife, 2011)
Novel fuels	May be compared to the definition of alternative fuels. A term often used in the aerospace industry to represent biofuels, Fisher-Tropsch fuels, etc.
Biomass	Renewable energy that refers to organic material from plants and animals, including agricultural and municipal waste products(European Biomass Industry Association, 2006)
Biofuel	Fuel produced from renewable biological resources such as plant biomass

	and treated municipal and industrial waste (European Biomass Industry Association, 2006)
First generation biofuel	Fuel derived from sources such as starch, sugar, animal fats and vegetable oil (CURES Network & International Steering Committee, 2010)
Second generation biofuel	Fuel derived from lignocellulosic crops (CURES Network & International Steering Committee, 2010)
Third generation biofuel	Fuel derived from algae oil (Coyle, 2010)

1.2.2 Identification of future potential bioenergy supply

In section 1.1.3, it was reported that the turbine must be located in the country where the fuel is produced. This section shows that the potential bioenergy supply is dependent on the geographical context through a review of important publications that focused on assessing the potential bioenergy supply. First, it is necessary to define how supply potential may be addressed in several ways such as shown in Table 1.3.

Table 1.3: Definition of different types of potential bioenergy supplies (Smeets et al., 2007) and (European Biomass Industry Association, 2006)

Potential	**Definition**
Theoretical potential	The theoretical maximum potential is limited by factors such as the physical or biological barriers that cannot be altered given the current state of science. It includes bioenergy production from land, rivers, seas and oceans.
Geographical potential	The fraction of theoretical potential that is limited by the area of land.
Technical potential	The fraction of theoretical potential that is not limited by the demand for land for food production, housing infrastructure and forest conservation based on an (assumed) level of advancement of agricultural technology.
Economic potential	The technical potential that can be produced at economically profitable levels.
Ecological potential	The potential that takes into account ecological criteria (e.g. loss of biodiversity or soil erosion).
Implementation potential	The fraction of the economic potential that can be implemented within a certain timeframe, taking into account institutional and social constraints and policy incentives.

In (Smeets et al, 2007), the bioenergy production potential for 2050 was first estimated by assessing at its technical potential using a bottom-up approach. Indeed, the bioenergy potentials are calculated with different key factors (e.g. land availability, demand for food and wood, biodiversity conservation needs, type of agricultural management) for all studied regions. The assessed factors, which differ from one region to the next, ended up providing regional production potentials that varied greatly. Figure 1-2 shows the primary results of the study and clearly illustrates the previous statement. This study, however detailed and precise, still reveals an important amount of uncertainty. Additionally, in light of the labour intensive data collection process, the methodology may prove that a less complex approach could be useful for a simple market assessment.

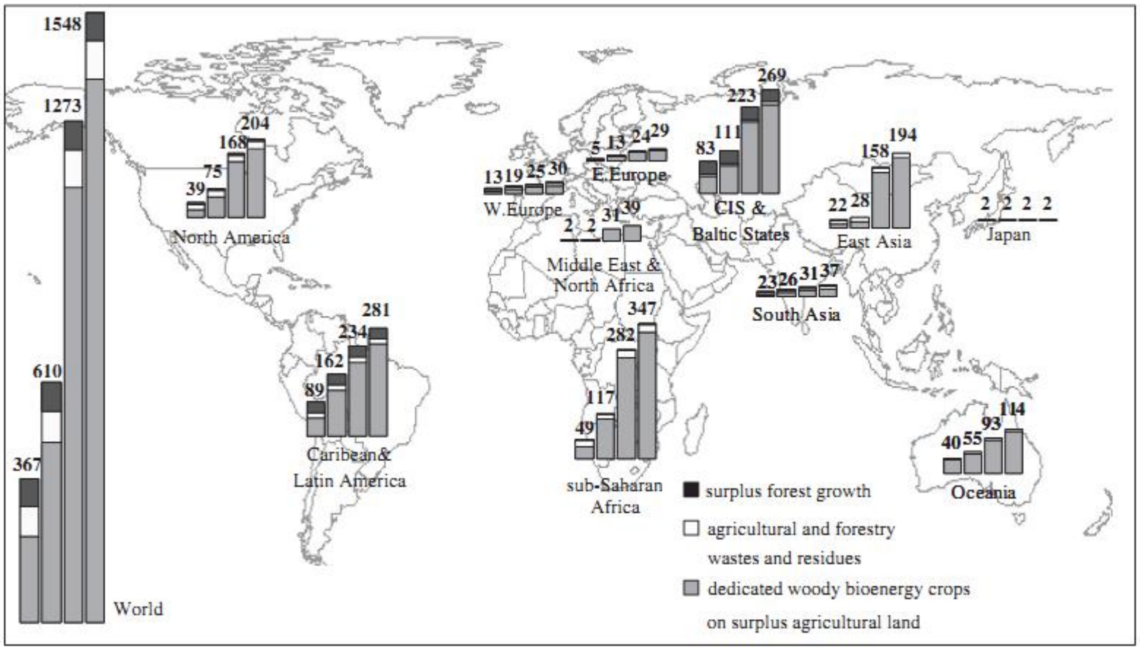


Figure 1-2: Total technical bioenergy production supply potential in 2050 (EJ/yr) (Smeets et al., 2007)[1]

In their previous report, (Smeets et al., 2004) used other particularities that are region-dependent while assessing the potential production of biofuels. Indeed, for each studied region, there were assessments on future biofuel policies, current production yields, relative feedstock costs, land yields, current biofuel consumption, etc. A review of the studies on the topic concluded that bioenergy demand is not only sensitive to biomass supply potential but also to total energy demand and the competitiveness of alternative energy supply options (Berndes et al., 2003). It was also noted that these bioenergy supply assessments did not consider the possible environmental impacts generated by resource use. Finally, the review showed that the studies came to different conclusions with regards to the potential supply in different regions since

[1] Reprinted from *A bottom-up assessment and review of global bio-energy potentials to 2050*, Vol. 33, Edward M.W. Smeets, André P.C. Faaij,Iris M. Lewandowski,Wim C. Turkenburg, A bottom-up assessment and review of global bio-energy potentials to 2050/Chapter 6. Total potential bioenergy supply in 2050, p.91, Copyright (2006), with permission from Elsevier.

different factors were used for in the assessments and many uncertainties therefore arose, especially in terms of the assumptions.

1.2.3 Bioethanol production

Ethanol is a straight-chain alcohol (C_2H_5OH) that has many known applications (e.g. alcoholic beverages, solvents, fuel). Bioethanol may be produced from different types of biomass, from **sugars** (e.g. sugarcane, beets), **starches** (e.g. corn, wheat, cassava) and **cellulose** (e.g. corn stover, switchgrass, willow). Cellulose produces what is commonly referred to as **cellulosic ethanol** and has recently gained in popularity because it does not directly compete with food crops. This is so since cellulosic biomass is not intended for food production.

Ethanol production involves these main steps (Wooley et al, Ruth, Sheehan, & Ibsen, 1999):

1. Pre-treatment (mechanical and/or chemical and/or thermal)
2. Saccharification (hydrolysis)
3. Fermentation
4. Purification and product recovery

It is important to note that the pre-treatment and saccharification steps may vary depending on the type of biomass and operation conditions. When producing ethanol from sugar, saccharification is not necessary. However, the process is essential when producing ethanol from starches. For cellulosic ethanol, the process is even more complex, since the breakdown of the cellulose from the lignin and hemicelluloses (other components in lignocellulose) requires either an enzymatic or chemical hydrolysis of the biomass in order to exert the glucose necessary for the fermentation process (CURES Network & International Steering Committee, 2010).

For sugarcane ethanol, the biomass is collected, washed, chopped, shredded and fed to several mills where a juice containing 10-15% of sucrose and bagasse (i.e. remaining crushed cane) is extracted. The juice is sterilized and then converted into ethanol while in contact with yeast, according to this simple chemical reaction:

$$C_{12}H_{22}O_{11} + H_2O \rightarrow 4\,C_2H_5OH + 4CO_2$$

Then, in a distillation unit, the ethanol is recovered. In this case, the lignin part of the sugarcane is recovered but only to produce the heat and power required in the ethanol production process (Jungbluth and Faist Emmenegger, 2007).

When ethanol is produced from lignocellulosic biomass, **biochemical** or **thermochemical** process pathways may be used. Just as with sugarcane, the first pathway requires mechanical pre-treatment. However, chemical and thermal pre-treatments are necessary as well. The second pathway has the advantage of being able to process all type of feedstocks (e.g. from wood) but generally requires more complex and expensive systems. In this approach, heat and chemicals are used to break the biomass into syngas (a mixture of carbon monoxide and hydrogen) and reassemble it into products such as ethanol. In the gasification process, the biomass is first dried and then directly fed into a gasifier where the lignocellulose is decomposed and partial oxidized by air. The resulting syngas has many impurities (tars, ammonia, sulphur, etc.) that must be eliminated in several scrubbing and conditioning units, from which the purified gaseous fuel exits. Finally, the fuel is fed into a reactor where the Fischer-Tropsch (van Ree et al., 2005) process converts the CO and H_2 into hydrocarbons of different lengths, and a final separation process enables the extraction of the different chemicals (ethanol, methanol, etc.). Below are the chemical reactions associated with the FT process:

$$\begin{aligned}
&nCO + 2nH_2 \rightarrow (-CH_2-) + nH_2O \\
&nCO + (2n+1)H_2 \rightarrow C_nH_{2n+1} + nH_2O \\
&nCO + (n+m/2)H_2 \rightarrow C_nH_m + nH_2O
\end{aligned}$$

Other thermochemical processes such as pyrolysis, direct combustion and hydrothermal upgrading (HTU) must also be mentioned for this production pathway. However, they are less often used than gasification, especially in full-scale plants. Finally, if the plant is dedicated exclusively to ethanol production, then thermochemical processes are not well suited since they are rather meant as platforms for fuel production for different market applications, similar to a refinery (NREL, 2007).

1.2.4 Biogas production

Biogas is a biologically generated fuel that can be produced from organic waste and mainly consists of methane (CH_4), carbon dioxide (CO_2) and a mix of trace gases including nitrogen, hydrogen sulfide (H_2S), hydrogen and others. It can be used for internal (on-site) heat or electricity demands, and, if purified, it may be injected directly into the natural gas grid or used as a transportation fuel. It is generated when biomass undergoes **anaerobic digestion** (i.e. biodegradation in an oxygen-free environment).

The types of substrates that may be used to generate biogas include municipal waste, agricultural residues, manure, sewage sludge, slaughter wastes, ley crops, grass, etc. Biogas plants using co-fermentation processes (i.e. co-digestion of liquid manure and biowaste) have shown increased yields. The quantity and quality of the biogas depend on the composition of the feedstock (% organic matter and moisture), residence time, temperature (thermophilic, mesophilic), and quality and quantity of co-substrates (Jungbluth and Faist Emmenegger, 2007). The anaerobic process involves of four stages:

1. Hydrolysis
2. Acidogenesis: The most important phase (i.e. acidogenetic fermentation) in which acetate is the main end product and volatile fatty acids, CO_2 and H_2 are produced.
3. Acetogenesis: Phase to break down the volatile acids into to acetate and H_2.
4. Methanogenesis: Phase in which acetate and H_2 are converted to CH_4 and CO_2.

In anaerobic digestion, the type of plant dictates process design. When the biogas is used locally, it can either be used in a boiler for heat generation only or in a turbine for combined heat and power (the current trend in biogas plants). The internal functioning of a biogas plant may be complex: the fresh substrate is fed into a large amount of digested matter in a tank, the tank is aerated for 1-2 days, and the matter is degraded anaerobically reaching its maximum yield at 10-14 days and then decreased to reach a plateau of half its maximum production yield. In order to keep a constant biogas production flow, several tanks are operated in parallel and fed at different time intervals (European Biomass Industry Association, 2006).

It should be noted that the energy efficiency of a biogas plant is very dependent on factors such as feedstock type, raw material transport distance, means of transportation, raw material and digested residue management and conversion pathways.

1.2.5 Syngas production

Syngas, or synthetic gas, is a fuel mix with varying amounts of hydrogen (H_2) and carbon monoxide (CO) and small amounts of carbon dioxide (CO_2), steam (H_2O), sulfur compounds of hydrogen sulfide (H_2S), carbonyl sulfide (COS), ammonia and other trace contaminates. The exact composition of the fuel depends on the type of feedstock and gasifier reactor system that is used. The gasification process was previously discussed in the ethanol section but will be detailed further here (CURES Network & International Steering Committee, 2010).

Gasification is the conversion by partial oxidation (with air, oxygen or steam) at elevated temperature (600-1000 K or more) of a carbon-rich feedstock such as biomass or coal into a gaseous fuel. In the first production stage, the biomass is partially burned to form producer gas and charcoal. In the second stage, the carbon dioxide and water produced earlier are chemically reduced by the charcoal, forming carbon monoxide and hydrogen. In the case of air gasification, a low heating value gas is produced (HHV: 4-7 MJ/Nm3). However, when using oxygen, a medium heating value (10-18 MJ/Nm3 higher heating value) is produced (European Biomass Industry Association, 2006). Three types of gasifiers are generally used for this application: fixed bed, fluidized bed and entrained flow. The fixed bed gasifiers are of smaller scale and come in two types: down-draft or up-draft. The oldest and most popular gasifier in commercial operation in the US and worldwide is the Lurgi dry ash gasifier, which is a down-draft fixed bed gasifier. It was estimated that about 75% of the global coal gasification capacity is generated by Lurgi gasifiers. Fluidized gasifiers require sizes of about 15MW in order to be economically viable but are practical when dealing with agricultural biomass, since the producer gas has low tar, sulphur and chloride content. As for entrained flow beds, they are infrequently used in commercial operations at this time (Bartone and White, 2007).

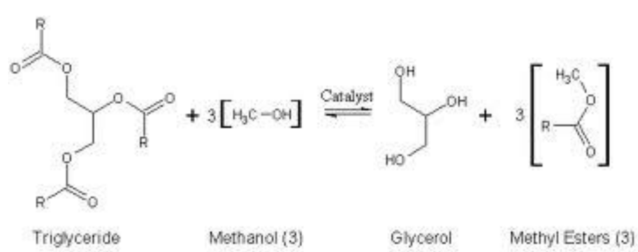
1.2.6 Biodiesel production

Biodiesel is an oil- or a fat-based fuel consisting of long-chain alkyl (methyl, propyl, ethyl) esters. It may be derived from virgin oils (e.g. rapeseed, soybean, palm and coconut oil), waste vegetable oil, animal fats (e.g. tallow, lard, yellow grease) and algae. Biodiesel is usually blended with petroleum-based diesel, and blends with less than 20% biodiesel are used in diesel equipment with no or only minor modifications. The biodiesel production from the oil or fat materials is the same as that for all types of raw material. The difference lies in the steps leading up to the oil or fat production.

1.2.6.1 Palm oil methyl ester (POME)

Palm oil is derived from fresh palm fruit bunches (PFB) which, when cultivated, are sent to the oil mill. The process typically used for PO production in Malaysia and Indonesia is wet milling. PFB are characterized by three main components: the mesocarp (oil and fibres, source of PO), endocarp (shell) and endosperm (source of palm kernel oil (PKO) and palm kernel meal (PKM) (Jungbluth and Faist Emmenegger, 2007). The bunches are fed to digestors, pressed and passed through a purification unit in order to extract the oil. The co-product from this stage is press cake, which undergoes a series of processes to recover kernels which, with further processing, will produce PKO and PKM. The rest of the PFB (shell, fibre, and empty fruit bunches) are burned in boilers to obtain the process power and heat. All energy surpluses may be sold to the grid for extra revenues (Jungbluth and Faist Emmenegger, 2007).

As mentioned earlier, the production of methyl ester and glycerine from palm oil is similar to the process that other vegetable oils or animal fats undergo. This is called the transesterification process, in which an oil or a fat is reacted with a monohydric alcohol in the presence of a catalyst as follows:



Different pathways for transesterification are possible: base catalyzed, direct acid catalyzed or oil conversion into fatty acid and then biodiesel. However, most biodiesel production is carried out through base catalyzed transesterification, since it is the most economical process and requires the lowest temperatures and pressures.

Finally, in the case of biodiesel from animal fat feedstock, the raw material must go through a rendering process, which leads to the production of value-added products (e.g. fatty acids) from animal tissue, usually from slaughterhouse waste. The fatty material is ground and then undergoes heating, percolation and pressing treatments to yield the desired purified form of fat.

1.3 Life cycle assessment

As mentioned previously, prior to the start of the project, it was decided that life cycle assessment (LCA) would be used to evaluate the alternative fuels. This section describes the methodology and its applications.

1.3.1 Definitions and applications

The International Organization for Standardization (ISO) defines life cycle assessment (LCA) as a compilation and evaluation of inputs, outputs and the potential environmental impacts of a product system through its life cycle (ISO, 2006). The life cycle of a product is defined as the consecutive and linked stages of a product system, from the extraction of raw materials or generation of renewable resources until its final disposal. LCA is a methodological tool that aims to quantify the potential environmental impacts associated with each stage in a product's life cycle. It is a scientific decision-support tool for which ISO standards have been set out (ISO 14040 and 14044). It is one of many tools used for better sustainable development practice and has many applications. For example, LCA may be used to:

- Identify hotspots in a product life cycle to improve environmental performance;
- Develop environmental standards based on life cycle thinking;
- Facilitate environmental management within a corporation or a government or non-government organization as a decision support tool;
- Help market a product with environmental benefits, ecolabelling and environmental product declaration (EPD);

- Guide public policies.

1.3.2 LCA methodology

As seen in Figure 1-3, the ISO standard defines the four steps in an LCA study described in this section. The first step to define the goal and scope enables the practitioner to determine the extent of the study and answer certain questions: *For whom is the study intended? Why was it conducted? What is the required level of detail? What are the objectives?* In the end, the following elements must be included (Jolliet et al., 2005):

- **Function of the system**. The function of the system is the basis of comparison of different systems. It represents the characteristics of the system's performance and must be identical for all of the scenarios that are compared. For instance, to compare the combustion of different biofuels in power plants, the function is electricity production.
- **Functional unit.** The measure of the function of the studied system and the reference for all input and output flows. To follow the previous example, the functional unit could be the production of one MJ of electricity (equivalent to 0.2778 kWh).
- **Reference flows**. The quantity of products required to fulfill the functional unit. They generally differ from one scenario to the next. Still following the example, the reference flows pertain to *y* amount of fuel (e.g. wood, biofuel) and a fraction of the infrastructures of a power plant.
- **System boundaries**. In order to properly define the system boundaries, the practitioner must refer to the type of assessment and goal of the study and determine the inclusion criteria so as to decide which processes are to be excluded. By definition, system boundaries include all the processes necessary to the function of the system. Usually, a preliminary screening is carried out in a simplified LCA in order to identify the important processes and the less significant ones that could be omitted.
- **Impact categories and impact assessment methodology**. There are many types of impact assessment methods. The selected method must be identified in the study along with the categories used to interpret the impact results.
- **Data quality demands.** These demands enable the practitioner to guide the data collection process and are an indicator of the reliability of the results. The three main aspects of data quality are relevance, reliability and accessibility.

- **Assumptions and limitations.** Assumptions and limitations must be clearly determined for the study to be as transparent as possible and may be the result of choices made when defining the goal and scope. For example, they may refer to the allocation method or to the fact that the results are only valid for a certain geographical area or time period.

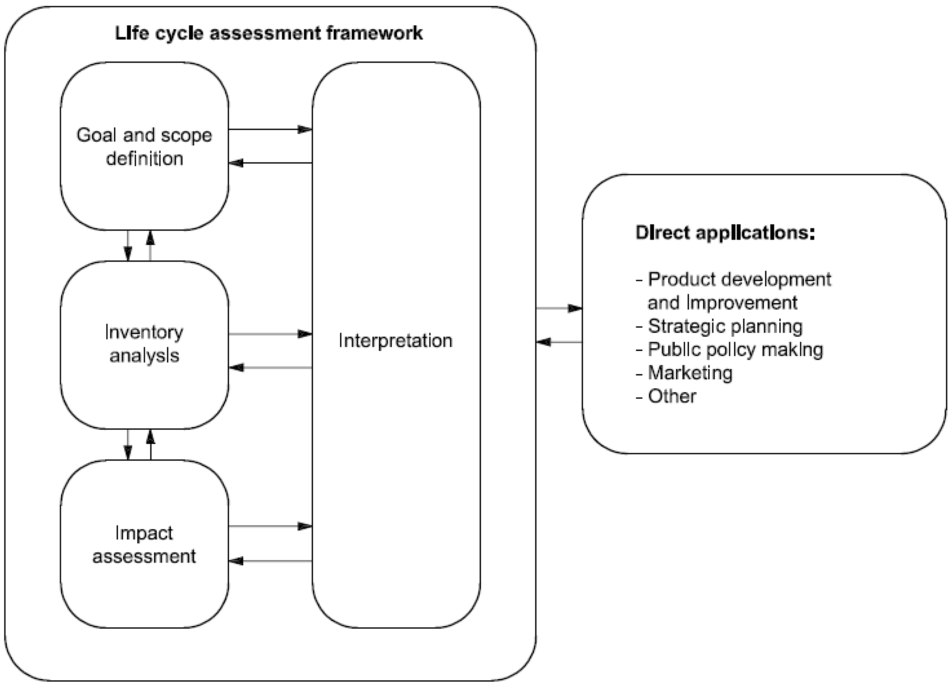


Figure 1-3: LCA framework according to the ISO14040 standard adapted from (ISO, 2006)

The second step in the LCA is the inventory analysis, which quantifies the emissions in air, water and soil, the extraction of renewable and non-renewable raw materials as well as the land use required to fulfill the function of the system. The data is first gathered for the system defined in the previous step. However, because LCA is an iterative process, adjustments should be made to meet the study goals as the system is defined in more detail. Once the product system is defined, data collection begins. This step is often the most labour intensive and should generally include as much site-specific data (primary data) as possible since it is more precise and of better quality. Generic data (secondary data) may also be used as average or background data in order to complete the system flows. Generic data consists of information from databases such as ecoinvent (Frischknecht and Jungbluth, 2007) that are especially designed for LCA. This data is then entered and compiled in software able to cumulate product system inputs (natural resources, energy and land use) and outputs (emissions) per functional unit. These flows are known as elementary flows, whereas the economic flows refer to the flows linking unit processes throughout a product's life cycle.

The third step of an LCA is impact assessment. This step aims at taking the inventory results and converting them into potential environmental impacts. In order to link these elementary flows to environmental impacts, three steps are necessary: the classification of emissions and extractions, intermediate characterization and damage characterization. Figure 1-4 represents the methodological structure for the IMPACT 2002+ method. Other methods such as ReCiPe, TRACI, LUCAS or Ecoindicator 99 may be used. Ultimately, the choice of method depends on the goals and specifications of the study.

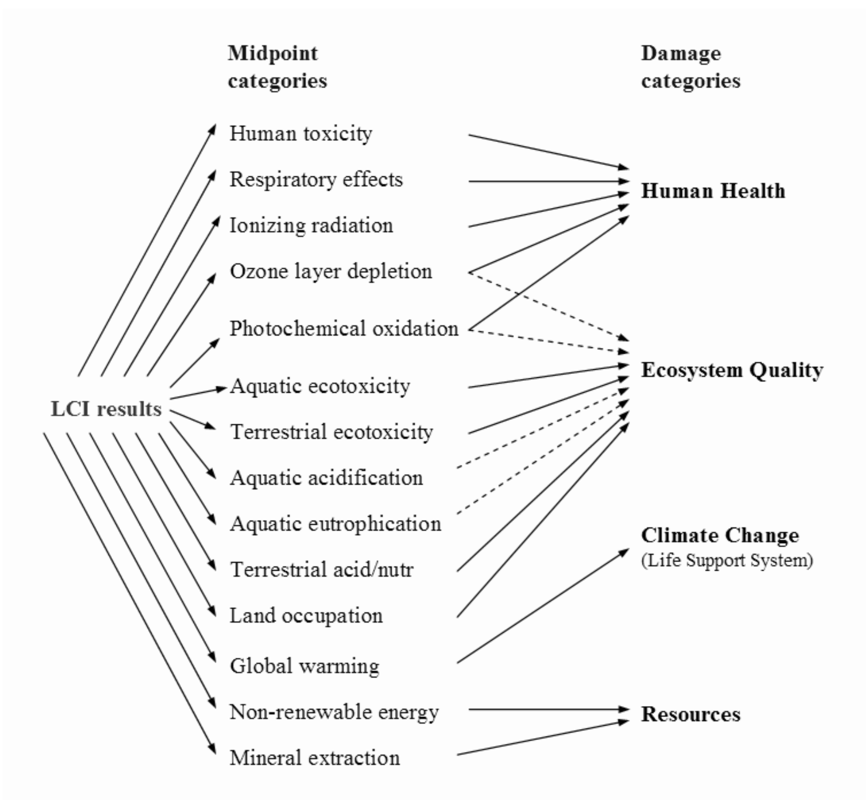


Figure 1-4: Overall scheme of the IMPACT 2002+ framework adapted from (Jolliet et al, 2003)

The fourth and final step is the interpretation of the results, which allows the practitioner to analyze the results, draw the appropriate conclusions, explain the limitations of the study and make recommendations based on the inventory and impact results (Jolliet et al., 2005).

1.3.3 Types of LCA

There are many types of life cycle assessments to meet different needs: consequential LCA (CLCA), attributional LCA (ALCA), retrospective and prospective LCA, dynamic LCA (D-LCA) and macroeconomic LCA (M-LCA). CLCA, ALCA and prospective and retrospective LCA are relevant to this study and described in terms of their definitions, applications and limitations in the following paragraphs.

1.3.3.1 Attributional vs consequential LCA

ALCAs attempt to answer "how are things (pollutants, resources and exchanges among processes) flowing within the chosen temporal window?'' while CLCAs attempt to answer "how will flows change in response to decisions?" (Curra et al., 2005)

ALCA will only describe the physical flows associated with the potential environmental impacts that are directly linked to the product system (i.e. the processes and material flows directly involved in the production, consumption and disposal of the product). When faced with a system with multiple outputs (co-products), allocation is necessary and must be based either on economic value, energy content, mass, volume etc. ALCAs have low uncertainty because the relationships between the inputs and outputs are generally stoichiometric. This accountancy-type assessment mainly applies when determining hot spots, EPDs and generic consumer information (Weidema, 2003).

Unlike ALCA, CLCA describes the impacts of a decision and all processes and material flows that are directly or indirectly affected by a marginal change in the output of a product through market effects, substitution, use of constrained resources, etc. Additionally, allocation is avoided by system expansion. A strong proponent of CLCA gives the following rationale for eschewing partitioning in favour of system expansion (Weidema, 2003): firstly, partitioning is arbitrary and does not consider the consequences of a changed amount of co-product on the producing process and, secondly, there is no assessment of the possible effect that a co-product may have on another product (effects of displacement). CLCA is a more complete type of assessment, since it takes more than the studied life cycle into account and examines how the environmental impacts are affected when the state is changed. CLCA considers the market effects of a product's production and consumption and has broader applications than ALCA, such as public policy making, social action plans and product development. CLCA is nearly always highly uncertain because it relies on models that seek to represent complex socio-economic systems that may include feedback loops and random elements.

In a CLCA, product substitution—meaning the replacement of a product, group of product or services with other products and services—is the object of the study. In this sense, since the product is process-specific, its substitution may result in a substitution of one or many processes. In order to assess a product substitution, it is necessary to identify the marginal (or affected) technology. The most popular methods for marginal technology identification, especially in the case of additional energy crop cultivation and electricity substitution, are described later in this chapter.

In this particular case, the definition and distinction between foreground and background processes could be important. In fact, several authors (Frischknecht and Jungbluth, 2007; Tillman et al. 1998) thought it rather useful for consequential assessments. A foreground process is a process whose production volume will be directly affected by the studied change, whereas a background process is a process whose production volumes will not be affected or only be indirectly affected (i.e. only through the market) as a consequence of the increase or decrease in demand as a result of the studied change. In this study, both processes will be determined.

Finally, it is important to note that there is controversy in the LCA community as to which type of LCA is preferable. Should reality be favoured over uncertainty by using CLCA? According to many authors, CLCA is the appropriate tool when using the results to guide policy or decision making (Brander et al, 2009).

1.3.3.2 Prospective vs retrospective LCA

In addition to choosing between a consequential or attributional assessment, the practitioner should also choose between conducting a prospective or retrospective LCA. The definitions of these options are much simpler and straightforward than ALCA vs CLCA. Table 1.4 should therefore provide sufficient information.

Table 1.4: Relationship between retrospective/prospective and attributional/consequential LCA adapted from (Weidema, 2003)

	Attributional	Consequential
Retrospective	Allocation of responsibility to past actions (Who shall we blame for the way things are?)	Causal explanation of consequences of past actions (What would have happened if we had or had not done this?)
Prospective	Allocation of responsibility for future actions to past actions (Who shall we blame for the way things will become?)	Causal explanation of likely consequences of future actions (What will happen if we do or don’t do this?)

1.4 Affected technologies and identification methods

As stated earlier, one of the main objectives of consequential LCA consists in integrating the affected technology -and the relative changes that took place- in the studied product system. This is also considered to be one of the most complex steps in carrying out a consequential LCA and can lead to the greatest uncertainty. Weidema (1999) uses the term *affected technology* for a technology that is affected by a small change in demand. The identified technology must therefore be included in the system boundaries, while unaffected technologies will be left out.

1.4.1 System expansion

System expansion is an important application of the identification of the affected technology. Indeed, when handling a co-producing process (e.g. agricultural system), the impacts related to the studied product must be isolated and, since impact allocation and CLCA are considered incompatible, the impacts of the substituted product(s) must be credited to the system. Figure 1-5: illustrates this practice, where the studied product is product A and product B' is either product B produced by an alternative process or a product substituting B. In the latter situation, the substituted product must be identified using methods that are explained in this section.

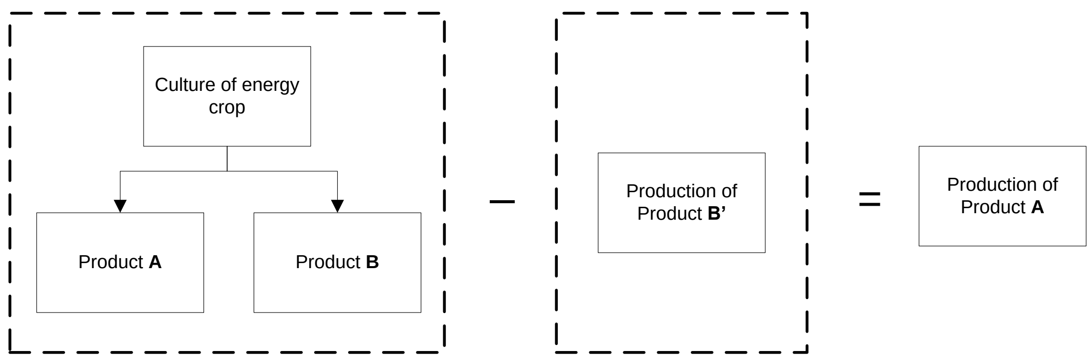


Figure 1-5: Agricultural system expansion

The system expansion approach depends on the type of multi-output process that is assessed and whether the products are considered to be impactful. Indeed, in some cases, the determining product (i.e. the product that determines the production volume of the co-producing process) is not the studied product, and the process impacts may not be allocated to it. When a product is determining for a process' production volume, then the process is affected by a change in product demand. The implementation of this methodology is detailed in section 2.4.2

There are three key rules for the correct implementation of a system expansion (see Figure 1-6):

1. Fully ascribe co-producing process A to determining co-product A. For this reason, when the studied product is not the determining product, no co-producing process impacts are allocated to it.

2. If co-dependent product B is fully used, product A will be credited for process D that is displaced by the dependent co-products. Additionally, intermediate process I must be assigned to the determining product.

3. When a dependent co-product (product B) is not fully used, the intermediate treatment will be ascribed to product C. Also, avoided waste treatment W will be credited to C.

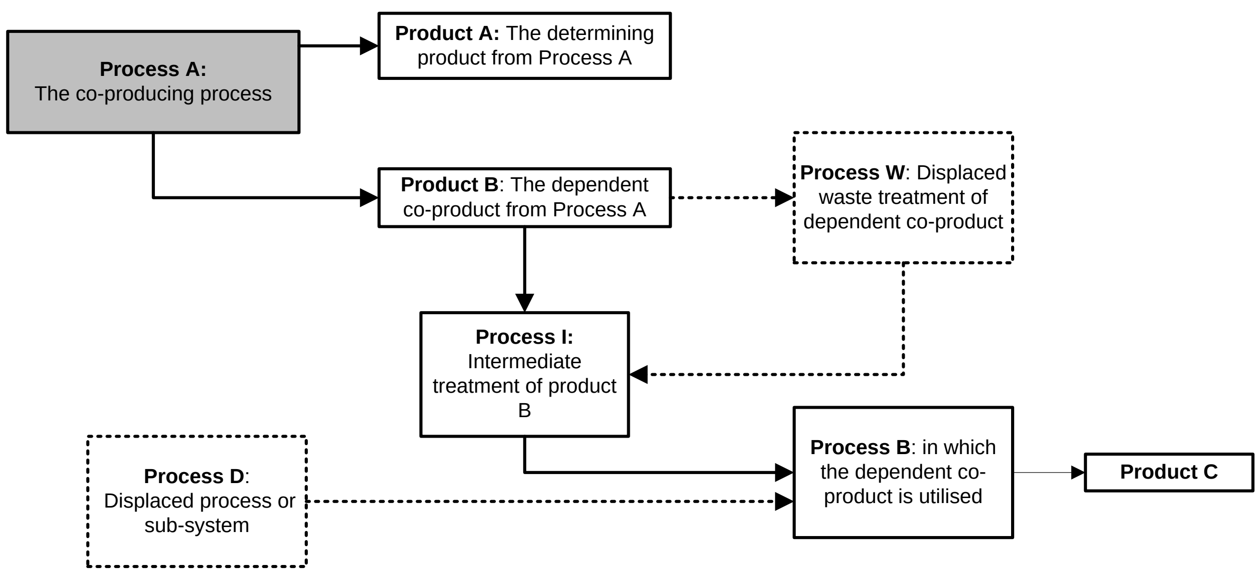


Figure 1-6: System expansion model for a co-producing process (valid when A or C is the product used), adapted from (Weidema, 2003)

For some co-producing processes, especially in agricultural systems, **knock-on** (i.e. incidental) **effects** may occur (e.g. when arable crops used for animal feed production impact other crops with the same purpose). Schmidt and Weidema (2008) published an applied case for palm oil production in which, in order to avoid co-product allocation, the authors considered the market application of palm kernel meal (i.e. animal feed). The two main properties of the feed were protein and energy sources for animals. The marginal substitutes for both fodder protein and fodder energy were therefore identified as soy meal (SM) from Brazil and barley (BL) from

Canada, respectively, meaning that the additional production of PKE will replace soy meal and barley production. However, since the production of soy bean yields oil and animal feed, a market reduction in oil supply is inevitable, leading to an increased demand for oil, which, in turn, requires additional palm oil production. In order to find an equilibrium in this ongoing process, an equation system such as the one in Figure 1-7 must be set out. For the demand of 1 kg of marginal oil, the amounts of each product required to maintain an equal supply of energy and protein source were calculated. In total, 1.007 kg of PO is required, and 0.028 kg of soy meal and 0.066 kg of barley are displaced.

$$
\begin{gathered}
\text{kg PO}\cdot\begin{bmatrix}\text{1 kg oil/kg PO}\\ \text{18.1 g prot./kg PO}\\ \text{0.096 FU/kg PO}\end{bmatrix}+\text{kg SM}\cdot\begin{bmatrix}\text{0.233 kg oil/kg SM}\\ \text{430 g prot./kg SM}\\ \text{1.20 FU/kg SM}\end{bmatrix}+\text{kg BL}\cdot\begin{bmatrix}\text{0 kg oil/kg BL}\\ \text{92 g prot./kg BL}\\ \text{0.95 FU/kg BL}\end{bmatrix}=\begin{bmatrix}\text{1 kg oil}\\ \text{0 g prot.}\\ \text{0 FU}\end{bmatrix}\\
\Downarrow\\
\text{kg PO}=1.007\\
\text{kg SM}=-0.028\\
\text{kg BL}=-0.066
\end{gathered}
\tag{1}
$$

Figure 1-7: Equation system to calculate the required amounts of crop to meet the demand for 1 kg of marginal oil, where FU represents a Scandinavian feed unit for energy content (Schmidt and Weidema, 2008)[2]

1.4.2 General method to determine affected technologies

The most recognized work to identify affected technologies is (Weidema, 2003). The method enables practitioners to identify several suppliers that would potentially be affected by a change in demand. These suppliers are dependent on market conditions and competitiveness, rendering them specific to a technology and/or geographical location. The underlying assumption of this method is that one or several suppliers have a fully elastic production while others have inelastic productions (i.e. a constraint that renders the technology unaffected by a change in demand). The following five steps are used to determine a marginal (affected) technology according to (Weidema, 2003):

[2] Reprinted from *Shift in the marginal supply of vegetable oil* ,Vol. 13, Issue 3, Jannick H. Schmidt, Bo P. Weidema, *Shift in the marginal supply of vegetable* / 3.2 Product system of palm oil applying system expansion in order to avoid co-product allocation, p. 238, Copyright (2008), with permission from Elsevier.

1. Identify the scale and time horizon of the studied changes.

2. Identify the affected market.

3. Identify the market trend.

4. Identify the production constraints.

5. Identify the suppliers/technologies that are most sensitive to changes (affected technologies that are the most and least competitive in expanding or contracting markets, respectively).

In order to identify the time scale, one must determine whether the studied system affects an existing production capacity (short term) or capital investments (long term). If it is acknowledged that a whole market is affected by a change in demand, then the affected technology must be identified. In this case, the practitioner must assess whether the market is increasing or decreasing. In the case in which the market is increasing, the most competitive technology is the affected technology, since it is privileged on the market and its use (or implementation) is prevalent, causing it to react to changing demand. When the market is decreasing, the least competitive technology is the affected one, since these units are expected to be decommissioned for newer and more efficient options. However, for either an increasing or a decreasing market, the affected technology must be unconstrained, since it must be able to adapt its production (and capacity) to the market demand. In order to determine whether a technology is constrained or not, we must examine different types of constraints, which may relate to nature (e.g. amount of water available in a region), quality (e.g. quality of a product), or politics (e.g. emission limits, quotas). It is also important to assess whether a co-product would be missing from a change in production (Weidema et al., 1999). Finally, if the technology is shown to be constrained, then it may not be considered to be potentially affected. In addition, more than one technology may be affected. To manage this ambiguity, practitioners must carry out sensitivity analyses.

As previously mentioned, a different type of approach to CLCA may be discussed at this point. Indeed, according to Dandres et al., the previously defined methods for conducting CLCAs could only be applicable to the assessment of marginal variation impacts on small systems. However, to study a large perturbation on a large system, such as a substantial substitution of electricity from fossil fuel to energy from renewable resources, the CLCA method must be adapted (Dandres et al., 2011). The method developed in this publication is a macroeconomic LCA (M-LCA), which is a computable general equilibrium model that takes price variations and non-linear effects on each economic sector into account. Indeed, it was demonstrated that all economic sectors should be studied, since there are direct and indirect interactions between the bioenergy and economy sectors that are not negligible. Basically, this method makes it possible to demonstrate how other sectors may be affected by a change in European bioenergy policy due to the perturbation of world goods production caused by variations in raw materials extraction. However, this method has proven to be very time consuming and data intensive. An LCA practitioner assessing a scenario with more modest consequences would not choose this method. In addition, the method should be used to model the impact of decisions that significantly impact a large system (which is not the case in this study).

1.4.3 Indirect impacts related to constrained resource use

This section aims to illustrate how indirect impacts arise with the use of constrained resources, since the upstream process cannot adapt to the new demands of the constrained resource. Two important government studies conducted for the US and UK governments, respectively, assessed the production of biofuels from different constrained feedstock sources.

The US.EPA calculated the relative life cycle GHG emissions of non-food crops to meet the GHG reduction target set out in the Energy Independence and Security Act (2007). This study evaluated biofuels from waste products such as MSW, rendered fats and waste oils and corn stover feedstock (US.EPA, 2009). The approach assumed no land use changes from these biomass sources since they do not compete for domestic crop acreage because the LUC impacts should be attributed to the primary function of the product (e.g. production of animal for their meat) and not the waste or by-product used for biofuel production. In this case, the feedstocks are considered constrained: if they were produced for a different application such as bio-electricity, their availability on the market would be lessened and an additional substitute product would have to be produced to compensate.

The second study was commissioned by the Renewable Fuels Agency and the Department for Energy and Climate Change (UK) in order to quantify the indirect GHG impacts from biofuels from waste, residues and by-products (Brander and Hutchison, 2009). The research was done specifically for these feedstocks, since it was concluded that important indirect effects would come from their use in bioenergy applications. The key findings of this study are that feedstocks with current applications generate significant indirect GHG effects, and the use of biomass that is usually disposed of has positive GHG effects, since end-of-life impacts of the biomass are avoided.

For constrained resources, the general line of thought is that these materials have inelastic supply since they cannot respond to a change in demand due to the fact that their production is not determined by market demand but rather the demand for the primary product or for a precursor product (e.g. food, in the case of organic MSW). Essentially, if these sources of biomass can be used for alternate applications, their availability would be reduced for current users or waste systems, leading to a reduction in the amount of waste to be disposed of or the production of substitute materials—all of which generate indirect impacts.

1.4.4 Land use change impacts for energy crop-based fuels

The importance of considering the effects of GHG release due to land use change (LUC) has sparked debates on biofuels and bioenergy among LCA researchers and practitioners. However, according to the IPCC, approximately 17% of global GHG emissions are related to land use change. Generally, emissions related to ILUC are lacking in LCA studies, or at best are modeled without reasonable considerations for the cause-effect relationships between land acquisition and the resulting effects (Christiansen, 2011). Nowadays, CLCA is most often used for biofuel studies, since they include ILUC impacts. In fact, many studies have shown the significant contribution of GHG emissions from direct and indirect land use change generated by biomass production, and biofuel assessments should therefore take theses impacts into account (Searchinger et al., 2008). Cultivating new energy crops may disturb the soil's carbon storage in a negative way but could also be beneficial if the original land was of poor quality (i.e. degraded land) (Müller-Wenk and Brandão, 2010). The distinction between direct and indirect LUC is important and must be addressed. The basic definitions of LUC are as follows (Kim et al., 2008):

Direct LUC: Land use change occurs as part of a specific supply chain for a specific biofuel production facility.

Indirect LUC: Market forces produce land use change on land that is not part of a specific biofuel supply chain, including, for example, hypothetical land use change on another continent.

For direct LUC, the calculations are rather straightforward, and data may be found in several leading studies, such as the Renewable Fuel Standard program report (US.EPA, 2009). Sources not only show the types of land that have been used historically and whose area is expected to increase due to the cultivation of a given crop but also the associated GHG emission factors brought about by LUC. On the other hand, indirect LUC takes the markets affected by additional land use into account. Hence, determining the affected markets is very complex, and the different known methodologies for doing so are discussed later in this section. Several studies have attempted to model the affected markets, and the most widely recognized methods to identify affected technologies are presented here.

E4tech carried out elaborate work on several biofuels, and the authors looked at modeling direct and indirect LUC using a **causal-descriptive methodology** (Bauen et al., 2010), which may be described as a mapping out of the impacts generated by an increased demand for a given biofuel on the broader agricultural land and land use systems. The causal descriptive approach used in this study has shown that there are several options to attain the additional palm oil production required by each country identified as a marginal producer. E4tech assessed the following strategies:

1- Increasing the area of the palm plantation

2- Increasing palm yields on existing plantations

3- Relying on the substitution effect from co-products on the markets

Historical trends were analyzed to assess market changes, and market analyses were used to anticipate market interactions. Finally, expert opinion and literature findings were sought out. Data on the types of land expansion and CO_2 emission factors from different land use changes for a specific region and type of land were taken from the Winrock International data developed for the 2006 Intergovernmental Panel on Climate Change (IPCC). Since it is impossible to determine how a system will evolve, several scenarios were assessed for each biofuel. Varying parameters that were tested in the case of biodiesel from palm oil, for instance, include yield improvement, percentage of deforestation, type of land expanded onto, type of plantings, etc.

Another approach to indirect LUC calculations is the iLUC factors developed by Fritsche, whose work is based on a **simplified determinist approach** to land use change as opposed to data-intensive and rather opaque economic models (Fritsche, 2010). The iLUC factors represent average emissions per hectares of land used for globally-traded commodities. They were developed with statistical data on international trade and gross assumptions on current land use patterns and their capacity as adequate proxy to derive future global trends and potential GHG emissions from indirect LUC. This methodology has the advantage of simplicity, since the practitioner only uses an average factor for indirect land use. However, one might argue that the use of an average and *generic* factor does not sufficiently reflect the complexity of the market interactions and that these factors may not be derived for several other energy crops, since only certain commodities and regions were assessed.

1.4.5 Consequential approach to electricity substitution

This section aims to show that, while consequential modeling may provide state-of-the-art long-term perspective, a short-term approach may have its advantages. This paper demonstrates that: 1- short-term effects on the electricity system are noticeable, 2- considering the specificities of the energy sources is an important part of the identification process—especially the technical ability to adjust to a varying load—and 3- there is a need to determine various affected technologies and consider different possible scenarios.

1.4.5.1 Long-term affected technology

When identifying an affected technology based on a long-term perspective, it is important to consider responses such as changes in the timing and perhaps the nature of the investments in a new production capacity. The long-term affected energy source would therefore be the plant that would or would not be cultivated due to the changes in demand (Curran et al., 2005).

According to Weidema (1999), the long term is a period long enough to include the replacement of capital investments (as opposed to the short term). For the author, LCA typically assesses the changes that would affect a change in capital. This is even more pronounced in technologies that have short capital cycles or free market situations (e.g. where market signals play a major role when planning capacity adjustments). The adjustments that have short-term effects only (i.e. that affect the production outputs) arise only in exceptional circumstances or only constitute in-house changes.

In this particular work, Weidema applies the methodology to the European electricity scenario (Weidema et al., 1999). It was established that many technologies apply to base-load electricity generation in Europe (coal, hydropower, nuclear, natural gas, biomass, waste and wind power). In order to eliminate certain possibilities, the capacity increase constraints were assessed for each energy source. For instance, in the case of nuclear and hydropower, it was shown that political constraints from the European Commission as well as natural constraints (i.e. land and water availability) would exclude the options as new capacity installations in the next 10-15 years. In the end, having identified several unconstrained technologies, the ones with the lowest production costs were preferred. Weidema mentions that most long-term substitutions lead to some immediate short-term effects but that these are often for a negligible period as compared to the long term.

Many other studies on the identification of marginal technologies in the electricity market have been carried out and are in line with Wedeima’s work. Indeed, Mathiesen et al. described a new type of affected technology, the **dynamic marginal technology**, which is defined as a marginal technology able to adjust its operation to the demand on an hour-by-hour basis (i.e. load following). This technology is from a subset of what were previously referred to as marginal technologies (i.e. determined in Weidema’s approach). With this new approach, Mathiesen et al. bring up an original point by stating that some technologies did not have the technical ability to adjust themselves to the load and therefore cannot be considered as an adjustable marginal technology for electricity production (Mathiesen et al., 2009). An example of this is wind power that cannot adjust its operations to meet a change in demand but which was identified as a possible marginal technology in Weidema (1999). In the same work, Mathiesen et al. highlight the uncertainty related to Weidema’s method and the fact that it is inconsistently used by practitioners. However, acknowledging these uncertainties, the authors suggest that identifying only one marginal technology is inadequate for decision-making and recommend using different affected technologies for LCA modeling and relying on many realistic but different perspective when developing long term perspectives to overcome this obstacle.

1.4.5.2 Short-term marginal technology

This section demonstrates that there is a need to correctly estimate the short-term production affected by a change in demand since there is an interaction through the electricity market between capacity and production changes and that many technologies are therefore affected. Finally, the section shows that the short-term marginal technology may be identified by assessing the marginal costs incurred by the power plant.

Methodologies to determine the marginal source of electricity production for LCA purposes, which differ from Wedeima's approach, have been developed in recent years. Indeed, the debate on whether coal or natural gas constituted the marginal technology (Dones et al., 1998; Curran et al., 2005) led certain authors to consider different ways of identifying the marginal electricity. Lund et al. used a detailed **energy system analysis** (ESA) to do so and considered the fact that there is a distinction between marginal capacities (i.e. long-term change in power plant capacities) and marginal supply (i.e. changes in production given the combination of power plants). They explain that certain LCAs have even pointed to the fact that the capacity installation of a power plant would interfere with the rest of the energy system (Lund et al., 2010).since the plants are not all designed to run at full load. Essentially, their ESA serves to identify what they refer to as the *long-term yearly average marginal* (YAM) technology. The purpose of identifying the YAM was to provide a well-justified estimate of the actual production (i.e. short term) affected by a change in demand. Their hypothesis was that fluctuations of real-life energy systems create a situation in which the marginal source is neither coal or gas but a mixture of different energy sources. They achieved this by looking at how the energy system responded on an hourly basis (i.e. short-term approach) to find the long-term YAM. The final conclusion of their work is that the installation of additional capacities changes the production of other technologies because of the interconnection through the market system. The identification of one marginal capacity is therefore inadequate, and a series of technologies affected by the supply should also be identified.

According to another publication (Amor et al., 2011), the identification of the marginal power plant for environmental impact accounting may be done through **electricity market price** on an hourly basis (i.e. short term). Indeed, the electricity market price dictates when the plants will operate according to the former's so-called *merit order*. In reality, the electricity demand is met by a variety of energy sources (e.g. nuclear, coal, gas, hydropower, wind), which all have marginal costs. Electricity generation involves different types of costs: capital, operation and maintenance and fuel. In this context, **marginal costs** refer to the cost of producing an additional unit of electricity, which can be estimated to be the fuel costs (i.e. the combination of the fuel market price and the power plant's efficiency). The first power plants committed to the electricity market are those with the lowest fuel costs (and higher fixed costs), such as nuclear facilities. These plants are referred to as base load plants since they are practically always in operation. The plants with higher fuel costs but lower fixed costs (e.g. gas, oil) are operated last and in peak demand hours.

Finally, Amor et al. established the marginal power plant as the last plant able to operate to meet the electricity demand and adapt its output based on market conditions. The power market price is therefore the point at which the supply and demand intersect. This is illustrated in Figure 1-8, which shows the situation when the market price reflects coal plant fuel costs. At that given time, if there were a change in demand, the affected energy source would be coal.

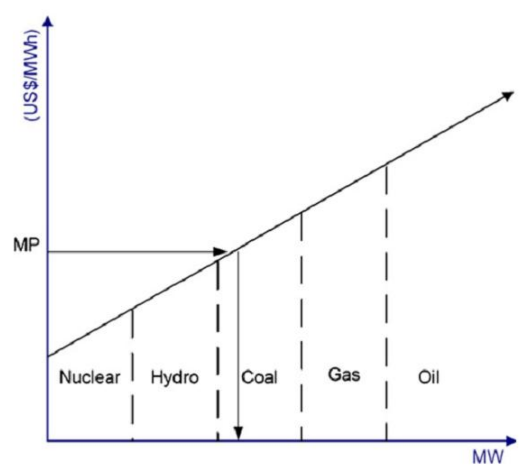


Figure 1-8: Supply curve to identify the marginal technology based on market price (Amor et al, 2011) [3]

[3] Reprinted from, *Electricity trade and GHG emissions: Assessment of Quebec's hydropower in the Northeastern American market* (2006–2008), Vol 39, Mourad Ben Amor, Pierre-Olivier Pineau, Caroline Gaudreault ,Réjean Samson, *Electricity trade and GHG emissions: Assessment of Quebec's hydropower in the Northeastern American market* (2006–2008) /Chapter 2.3. Identification of the marginal electricity production technology, p.1713, Copyright (2011), with permission from Elsevier.

In order to discuss the issue of the marginal source of electricity for LCA, a three-day workshop on electricity data for life cycle inventories bringing together experts from the LCA and electricity market fields was held (Curran et al, 2005). One of the key consensuses—similar to Mathiesen et al.'s conclusion—was that the type of power plant adaptability (baseload, semi-baseload and peak load) must be taken into account in order to define the response to demand changes on the electricity system. Finally, it is possible to conclude from these studies that the future is most definitely uncertain and that the electricity market is dynamic and evolving. Uncertainty is therefore undoubtedly present and this even when using the most advanced models.

1.5 Conclusions of the literature review

This literature review introduced different types of LCA methodologies and GT characteristics. The possible use of alternative fuels for gas turbine applications and their geographic context were also detailed. Alternative fuel production pathways were presented as along with the different methodologies to identify marginal technologies. Considering the previous sections, the literature review led to the conclusions presented in Figure 1-9.

Conclusion 1: The turbine location should be that of the feedstock and fuel production location.
Sections:
1.1.3 Turbine Location (Geographical context of the study)

Conclusion 2: The alternative fuel supply potential depends on their geographical context.
Sections:
1.1.3 Turbine Location (Geographical context of the study)
1.2.1 Context and definition
1.2.2 Identification of bioenergy future potential supply

Conclusion 3: There are many methods and factors (e.g. land availability, policies, feedstock production, etc.) that may be used to evaluate the fuels future potential supply. Consequently, there is a necessity to evaluate the regions, fuels and type of feedstock in terms of potential supply and technical feasibility through the identified factors.
Sections:
1.1.3 Turbine Location (Geographical context of the study)
1.2.1 Context and definition
1.2.2 Identification of bioenergy future potential supply

Conclusion 4: Considering the application of the study (i.e. used as basis for decision making), and the systems assessed (i.e. alternative fuels for electricity generation) a consequential prospective LCA is necessary.
Sections:
1.3.4 Types of LCA

Conclusion 5: For alternative fuels from energy crops, the direct and indirect land use change impacts must be taken into account.
Sections:
1.4.4 Land use change impacts for energy crop based biofuels

Conclusion 6: When dealing with a coproducing process, a system expansion must be performed in order to follow consequential studies guidelines and avoid co-product allocation.
Sections:
1.4.1 Definition and uses
1.4.2 Identifying affected technologies

Conclusion 7: When dealing with alternative fuels from constrained sources, the indirect effects of using these types of feedstock must be taken into account since the products cannot adapt to their increasing demand.
Sections:
1.4.3 Indirect impact related to use of constrained resources

Conclusion 8: For electricity substitution, identifying the long term affected technology is uncertain What is more, identifying a single technology and dismissing the technologies that are affected in the transition period are simplifications that exacerbate this problem. Identifying short-term affected technologies can help reduce the uncertainty on the short the run although it does not provide information on changes in installed capacity. Finally, when identifying the long term affected technology, it is important to consider the specificities of the energy source that is substituted (e.g. load following capability).
Sections:
1.4.5 Consequential approach to electricity substitution.

Figure 1-9: Conclusions of the literature review and related sections

CHAPTER 2 METHODOLOGY

The overall methodology used for this study is summarized in Figure 2-1 and explained throughout this section. It covers the methodology to determine alternative fuel supply potential and defines the goal and scope of the project and the methodologies used to carry out the CLCA.

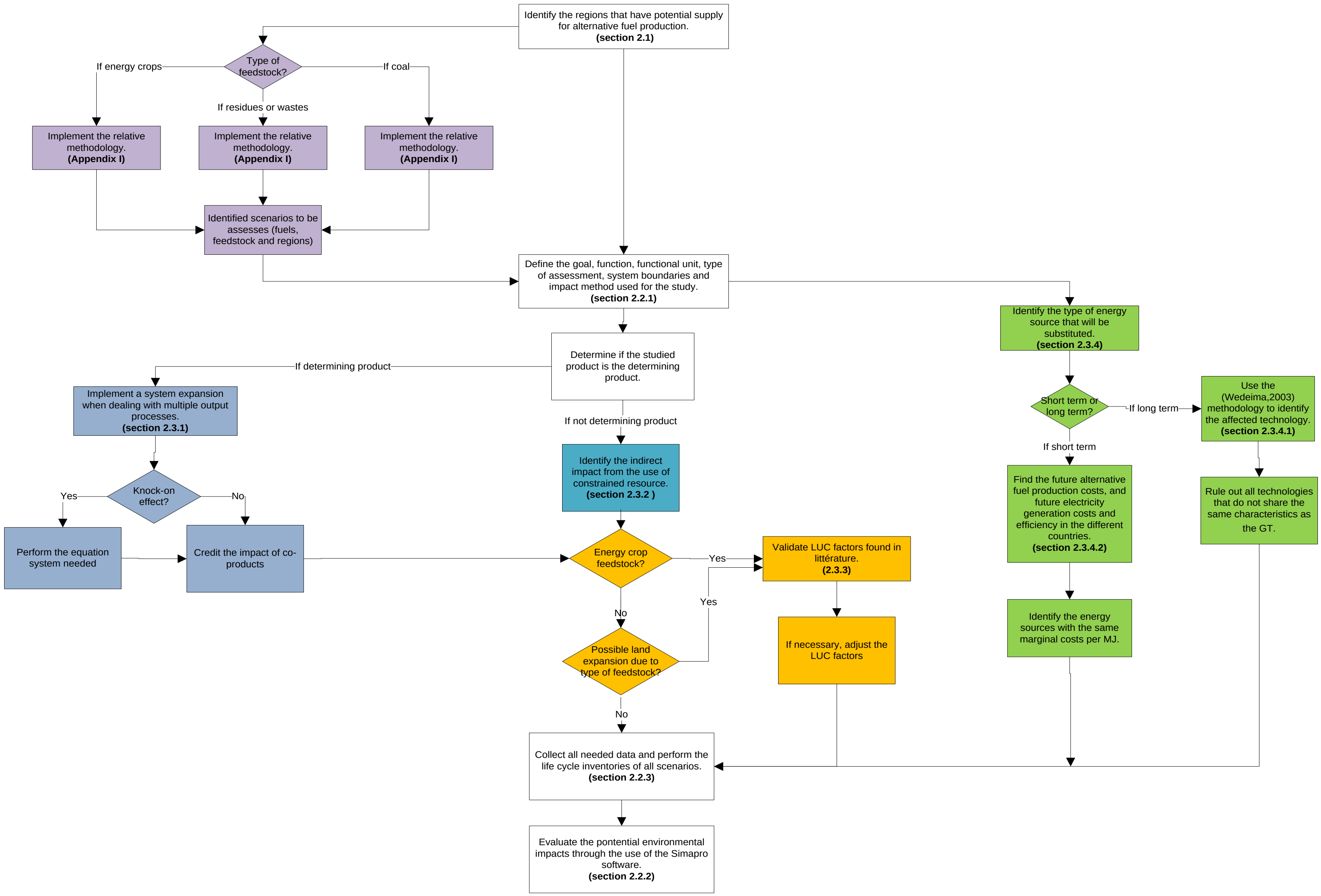


Figure 2-1: General project methodology

2.1 Results from alternative fuel supply potential assessment

This section covers national or international targets and policies associated with bioenergy production, production costs for the different alternative fuels, state of the technology in each regions and potential feedstock supply. The results are presented by type of feedstock category considered for the fuel production. Refer to APPENDIX VI for these results.

2.2 Future potential biomass and fuel supplies

The methodology outlined in the first section is described in **Error! Reference source ot found.**. Exceptionally, for this methodology section, the final results must be shown in order to continue the methodology section (see to Table 2.1). Indeed, the results show the alternative fuels that were selected and their geographical contexts. This information is essential to properly pursue the following methodologies pertaining to the CLCA itself.

As previously mentioned, this study explores alternative fuels that could be used in gas turbines: biogas, syngas, biodiesel and bioethanol, which were singled out by the industrial partner as fuels of interest for the corporation's future research and investments. It is important to consider the fact that the fuels all require different feedstocks that can be grown or extracted and produced in different regions of the world and therefore define the geographic context of the study. The methodology consists in identifying the regions—and relative feedstocks—that could potentially supply alternative fuel production. The methodology follows these key guidelines:

- Assess the feedstocks and regions for the alternative fuels of interest to the partner;
- Assess a broad range of feedstocks and regions;
- Pay particular attention to the potential for future commercial fuels (e.g. 2nd-generation fuels).

Finally, in order to identify the fuels, feedstocks and regions, a methodology to assess their future supply potential must be applied.

Table 2.1: Results for identified regions, feedstocks and fuels with the highest supply potential

Country	Feedstock	Alternative fuel
United States (US)	Corn stover	Bioethanol
United States (US)	Animal fat	Biodiesel
United States (US)	Coal	Syngas
Germany (DE)	Wood residues	Syngas
Germany (DE)	Manure (co-fermentation)	Biogas
Italy (IT)	MSW	Biogas
Brazil (BR)	Sugar cane	Bioethanol
Indonesia (ID)	Palm oil	Biodiesel
China (CN)	Coal	Syngas

2.3 Life cycle inventory

2.3.1 Goal and scope of the study

2.3.1.1 Goal of the CLCA study

As mentioned earlier, this CLCA has two objectives:

- Identify the alternative fuels with lower overall potential environmental impacts, considering their different feedstocks and geographical contexts.
- Identify the alternative fuel with the greatest potential benefit for electricity generation, as compared to the competing source of electricity generation in the relative countries.

2.3.1.2 Applications

A life cycle assessment is a decision-making tool, and its results will therefore be used as a backup for investments in different ecological technologies. These investments include the use of alternative fuels in the partner's gas turbines.

2.3.1.3 Target audience

The results will be used and reviewed by senior executives in the partner corporation in order to assess the relevance of the conclusions to future market strategies.

2.3.1.4 Function

The studied systems will have one primary function: to *supply electricity to the grid*.

2.3.1.5 Functional unit

The quantification of the studied function is based on the amount of electricity that is supplied. In this case, it is to *supply 1 MJ of electricity to the grid from a GT using alternative fuels*.

However, it should be noted that, even though all the flow calculations are based on generating 1 MJ of electricity, supplying 1 MJ of electricity to the grid from the GT (using alternative fuels) does not end up in an additional electricity supply to the grid but rather becomes a substitution of the identified marginal electricity with the gas turbine. Consequently, the potential environmental impacts resulting from this LCA are not accounted as impacts per MJ of electricity produced but rather as impacts resulting from the decision to generate 1 MJ with these alternative fuels.

2.3.1.6 Reference flows

The reference flows for each compared scenario vary. Indeed, the required volume of each alternative fuel to produce the MJ of electricity necessarily changes due to the different calorific values and efficiencies during combustion. It is assumed that the same GT infrastructure is required to produce the different types of fuels, since it has the same specificities no matter the type of fuel fed into it. However, the substituted electricity infrastructures may differ if the identified energy source is different.

2.3.2 Calculation method

The methodology used to assess the environmental impacts of the different scenarios is described in the following paragraphs.

2.3.2.1 Software

Simapro 7.2 was used to carry out the LCA. The software was created by PRé Consultants to calculate inventories and potential environmental impacts.

2.3.2.2 Impact assessment method

The IMPACT 2002+ impact assessment method was chosen for this study and is illustrated in Figure 1-4. It is a combined midpoint/endpoint (damage) approach that links the life cycle inventory results through 14 midpoint categories to four endpoint categories (ecosystem quality, human health, climate change and resource depletion),as follows:

- Human health: This category takes into account all substances with human toxicity effects (carcinogenic and non-carcinogenic), respiratory effects, and ionizing radiations as well as effects that contribute to ozone layer depletion. The severity of the health issues caused by these substances is quantified in disability-adjusted life years (DALY).
- Ecosystem quality: This category includes the impacts associated with aquatic and terrestrial toxicity, aquatic acidification and eutrophication, terrestrial acidification and land occupation. It is quantified in terms of potentially disappeared fraction of species over a surface and time period per kg of emitted substances ($PDF*m^2*yr/kg$).
- Climate change: The potential of each greenhouse gas is calculated in terms of kg of CO_2 equivalent, based on the data on infrared radiative forcing. The updated version of IMPACT 2002+ now quantifies the effects over a time period of 100 years.
- Resource depletion: This category takes into account the use of non-renewable energy sources and mineral extraction, quantified in MJ of energy.

The method was adapted in 2011 (version 2.2) and presently includes aquatic acidification and aquatic eutrophication in the ecosystem quality indicator, thus minimizing the number of impact categories presented in the results. The IMPACT 2002+ approach was first adapted from other previous methods, namely Eco-indicator 99 and CML 2002. It is an internationally recognized and respected method and has the advantage of having the climate change category as an endpoint, unlike the ReCiPe method, which aggregates the category into the human health category. The results of the study will, however, be compared to those calculated using the ReCiPe impact method in a sensitivity analysis.

Finally, the impact category on which the interpretation of the results is based is important. Indeed, the use of midpoint versus endpoint categories is often debated. However, (Bare et al., 2000) found that each options has its advantages and limitations. In this case, the endpoint impacts were chosen, since they are often favoured to support decision-making due to their greater relevance. Indeed, endpoint impacts lead to more understandable results and are also more valuable to aggregation. Since the results will be used by the partner for strategic decision-making, the endpoint impacts are the best adapted.

2.3.2.3 CLCA methodology

In keeping with consequential LCA guidelines, the following steps must be taken:

- Perform system expansions on co-producing processes
- Calculate GHG emissions related to direct and indirect LUC effects
- Determine the indirect impacts associated with the use of constrained resources
- Determine the type of electricity that is substituted due to electricity production by GT burning alternative fuels

See section 2.4 for further details on these steps**.**

2.3.3 Data collection

To complete the LCA, intensive data collection was required for all electricity generation life cycle stages through the alternative fuel fed GT and the identified substituted energy source. GT data was chiefly provided by the partner (see summary in Table 2.2).

Table 2.2: Data collection on gas turbine infrastructure and operation

Life cycle stage	**Type of data**	**Source**	**Comment**
GT package transport	Location of GT and GT package assembly and type of transport	Discussions with partner staff	
GT maintenance	Interval and type of materials replaced	Discussions with maintenance engineers at the partner's facilities	
Power plant site	Configuration of the plant and land occupation	Reports from other GT manufacturers	
GT component infrastructure	GT plans, weight, type of materials	Partner documents and discussions with partner staff	
GT package infrastructure	Type of equipment included in the GT, weight of the equipment	Reports from other GT manufacturers	
GT experience	Usual Trent 60 application, usual hours of operation and life time	Partner reports	
GT operation	Emissions of CO, CO_2, SO_2,VOC, hydrocarbons and particulates Water consumption Fuel efficiency	The industrial partner's software.	Some fuels were out of the specs for the software and may not be as reliable as data provided for usual GT use.

2.3.3.1 Data on the alternative fuel production

Alternative fuel production data was gathered from technical reports from institutions (e.g. National Renewable Energy Laboratory (NREL)), journal articles and databases such as FAOSTAT (Food and Agriculture Organization), the Food and Agricultural Policy Research Institute (FAPRI), etc. When necessary, mass and energy balances were also taken from the relative sources. When data could not be found, the ecoinvent 2.2 database was used to fill the gaps. In certain cases (e.g. POME and ethanol from sugarcane production), the processes were already very well defined in the generic database and only minor adjustments (e.g. land yields for the specified country in 2020) were made. The data collected is summarised in Appendix V.

2.3.3.2 Electricity substitution data

Electricity production data was also taken from ecoinvent and modified with data on power plant efficiencies for the relative countries based on (OECD and IEA, 2011) or (EIA, 2011a) information.

2.3.3.3 Fuel combustion emissions data

Fuel combustion emissions data either came from the literature on emissions from the combustion of syngas, biogas, biodiesel or bioethanol in turbines or from the software provided by the partner, whenever possible. The sources are referenced in the inventory tables in Appendix V.

2.3.4 Description of the scenarios

2.3.4.1 Product system and system boundaries

The diagrams of the product systems, delimiting the included processes and indirect impacts of the assessed systems, are in Appendix II.

2.3.4.2 System inventories

The inventories of every system assessed in this study are detailed in APPENDIX V. The elementary and economic flows are identified for each system. All modified ecoinvent processes are detailed and referenced.

2.3.4.3 Particularity of the biogas scenarios

There is an important distinction between the biogas scenarios and the others: the biogas production capacities of the digesters are not sufficient to supply the turbines for normal operation. Indeed, the existing facilities with the highest production capacities (i.e. agricultural digesters and municipal wastes digesters) would only supply some 30 to 35% of the amount of fuel required by the turbine. Consequently, the rest of the fuel would have to be natural gas.

2.4 Consequential LCA methodology

This section details the approaches pertaining to the consequential nature of the study. The four main methodology sections (see Figure 2-1) are:

1. The system expansion approach when in a co-producing process
2. The indirect impact assessment methodology when using a constrained resource
3. The direct and indirect LUC calculation method
4. The approach to identify the affected electricity source

It is important to mention that performing a system expansion consists in identifying how the production volume of the processes is affected by a change in demand. With this in mind, the other three methodologies all derive from a system expansion but for particular applications. Finally, the calculations and assumptions related to the methodologies to quantify the inventory for each system are presented in appendices III and IV.

2.4.1 System expansion approach for co-producing processes

As previously discussed, the approach for system expansion depends on whether or not the studied product determines the production volume of the co-producing process. This section discusses system expansion **when the studied product is the determining product**. The methodology applied if the studied product is not determining (e.g. biofuels made from waste or residues) is discussed in section 2.4.2.

Indeed, in this section, the studied product are the determining product, and the co-dependent products (i.e. bagasse, PKO, PKE, glycerin) are fully used. Therefore, co-producing process A and intermediate process I must be ascribed to studied product A. In addition, process D must be credited to the studied product (see Figure 1-6). In order to credit the impacts, it is possible to: 1- credit the impact of the production of a co-product substitute on the market or 2- credit the impact for the production of the same co-product produced by an alternative process.

Additionally, many agricultural systems are interlinked, and changes to one system (e.g. arable crops used for animal feed) will have **knock-on** (incidental) effects on other systems (i.e. other crops with the same purpose). In such cases, the use of a system equation, like the one illustrated in Figure 1-7, is required.

2.4.1.1 Sugarcane ethanol (Brazil)

The cultivation and production of sugarcane is a multi-output process. Though it has many co-products, sugarcane is the determining product. The following section explains how the impacts for each co-product were taken (or not taken) into account.

1. Sugarcane residue is currently burned in the fields and will probably eventually be left in the fields as source of soil nutrients (Bauen et al., 2010). The residue could be used instead of fertilizer, but, since it is not a consequence of the additional demand for sugarcane bioethanol, the reduced impacts cannot be assigned to bioethanol.

2. Stillage (or vinasse) is the main residue from the starch-to-ethanol fermentation process. It is a nutrient-rich product that is currently used as fertilizer to grow sugarcane. Stillage would therefore continue to be used for ethanol production. Consequently, no extra function is added to the system.

3. Bagasse (for heat and electricity) is used to produce the heat and electricity required in the ethanol production process. The heat produced is completely used in the process, however, some electricity surplus is generated and is usually sold to the grid (Jungbluth and Faist Emmenegger, 2007). The ethanol production process is therefore a multi-output process that generates both ethanol and electricity. In order to perform the system expansion, an impact credit for the surplus electricity production was added to the ethanol production process. To do so, the type of electricity affected had to be identified using the methodology detailed in section 2.4.4.

2.4.1.2 Biodiesel from palm oil (Indonesia)

As with the production of sugarcane ethanol, biodiesel from palm oil (including the cultivation stage) has many co-products. In this case, however, the system expansion was more complex due to the **knock-on effect** from the palm kernel expeller (PKE).

1. Palm kernel oil (PKO)

Since palm kernel oil may be further processed into palm oil, it was considered to be only an added source of palm oil, and no allocation is therefore required (Schmidt and Weidema, 2008).

2. Palm kernel expeller (PKE)

Palm kernel expeller is a co-product of palm oil production generated by palm kernel crushing. It is used as animal feed on the agricultural market. An added demand for palm oil production would therefore lead to an additional availability of animal feed on the market. In order to know which type of animal feed would be displaced from the additional PKE that is produced, the marginal fodder must be determined. Animal feed has two properties: source of energy and source of protein. Since both are traded on the global fodder market, the marginal protein and energy fodder were identified as soy meal in Brazil (Schmidt and Weidema, 2008) and wheat in Canada and EU countries (Bauen et al., 2010), respectively.

Based on the oil, energy and protein content properties of palm kernel meal, soy meal and wheat and by using the equation system in Figure 1-7 proposed by (Schmidt and Weidema, 2008), it is possible to determine the amount of each product that is affected by a given additional demand in palm oil biodiesel. The use of this equation system is necessary to take into account the **knock-on effect** of PKE replacing soy meal. Since soybeans are grown for the meal and not the oil, if they are no longer produced, there will be a reduction in the amount of soy oil produced. Hence, this soy oil must be replaced on the market by the affected marginal oil, which was assessed to be palm oil (Schmidt and Weidema, 2008). Thus, given the small proportion of soy meal that is substituted by PKE, an insignificant amount of palm trees will be planted. Again, this additional palm oil production produces more PKO and PKE, which ultimately displace more soy meal and so on. However, the effect finally converges to equilibrium, and an exact solution is found through matrix inversion.

Finally, the avoided or additional impacts of the additional palm oil production are summarized in Table 2.3.

Table 2.3: Difference in production of marginal commodities due to additional palm oil demand for the production of 1 MJ of electricity

Product	Additional production (kg)	Avoided production (kg)
Wheat	–	0.00354
Soybean	–	0.00275
Palm oil	0.00178	–
Glycerin	–	0.0667

3. Glycerin

Glycerin is a co-product from the transesterification process to produce biodiesel from vegetable oil. Consequently, the additional production of biodiesel from PO would produce an extra supply of glycerin on the market. It is assumed that the added glycerin would substitute synthetic glycerin on the market in all its usual applications (e.g. cosmetics, soaps, drugs, pharmaceuticals). The assumption is based on real market events. For instance, a DOW Chemical glycerin plant in Freeport, Texas had to close as a result of the recent opening of a nearby biodiesel plant. The same trend has been noticed in Europe as well (McCoy, 2011). It is also assumed that the glycerine from PO has the same properties as synthetic glycerin, and a displacement ratio of 1:1 between both types of glycerin was used. Consequently, the impacts credited to the system are the life cycle impacts of synthetic glycerin.

2.4.1.3 Biodiesel from tallow (USA)

Tallow

Tallow, a rendered form of animal fat, is not the determinant product in animal farming cultivation, but the biodiesel produced in the transesterification process is. Consequently, the same methodology and assumptions used for palm oil methyl ester are used here.

2.4.1.4 Syngas from coal

Syngas production from coal (the gasification process) generates two co-products: sulphur and cement slag. In the case of sulphur, it was determined that there is almost always a market for the product. However, in the case of slag, the potential market is highly dependent on the location of the gasification plant, even from one city to the next. Since the exact location of the turbine is not known, a sensitivity analysis was used to compare the two possible scenarios:

1- The slag is sold on the market as a road aggregate. There is therefore an impact credit for its production, and an additional credited is allotted for the slag's disposal.
2- The slag is not sold and there is no impact credit.

2.4.2 Indirect impacts from constrained resource use

The use of constrained resources has two different types of indirect effects. Firstly it changes the methodology used for implementing the system expansion. When no constrained resources are used, the system expansion is straightforward (Figure 1-5), whereas the methodology described in Figure 1-6 has to be taken when constrained resources are utilised. Indeed, in this case the feedstock used for alternative fuel production is not the determining product of the co-producing process but are rather the co-dependent product. Consequently, the co-producing process is not ascribed to the studied product, but intermediate process I and process B are (see Figure 1-6). Additionally, with the exception of tallow, they are not considered to be fully used and therefore do not depend on the co-producing process. Consequently, displaced process D or W have to be considered for every feedstock except tallow.

The second type of indirect effects from use of constrained resources differs for each type of feedstock and location. The former are explained in detail in this section.

2.4.2.1 Corn stover ethanol (US)

The impacts of corn cultivation are not taken into account here since the corn stover is not the determining co-product of the agricultural processes. Thus, the only processes taken into account were those related to the extra collection stages required for stover removal. Additionally, the removal of this agricultural residue is said to impact soil fertility due to the loss of the nutrients that the stover provided (Sawyer and Mallarino, 2007). Also, additional erosion could occur from the change in soil stability (Blanco-Canqui and Lal, 2009). It is possible to compensate for the nutrient loss by adding the impact of fertilizer production (relative to nutrient loss), which was adapted from literature data for different removal percentages. Indeed, when the removal rate is lower, it is considered to be a more sustainable farming practice, since nutrient loss and erosion are lower. However, the land area on which the removal will be carried out is greater, meaning that the machines will have to cover longer distances. It is possible to compensate for the impacts due to structural loss on corn yields by adding extra corn cultivation as an indirect impact. The calculations and illustration of why LUC are not taken into account are detailed in Appendix III.

2.4.2.2 Syngas from forest residues (Germany)

With regards to forest residues, the impacts of forestry are not allocated to the slash (i.e. forest residues) since an increased demand of these residues does not change the wood harvesting (i.e. not the determining product). However, the impacts generated by residue collection and transport are accounted for. In addition, slash removal impacts nutrient depletion, and the additional equipment for its removal causes soil disturbances. Both affect long-term site productivity. The indirect impacts include higher leaching rates, runoff and lower soil pH, which result in decreased tree growth. The calculation and illustration of why LUC are not taken into account are detailed in Appendix III. Also, it is important to note that a certain fraction of the residues are usually burnt. Since the residues would be collected, the scenario would avoid the impact of forest residues combustion on the harvesting and collection sites (Jones et al., 2010).

2.4.2.3 Biodiesel from beef tallow (US)

In the animal farming and slaughtering processes, the determining co-product is not tallow, and the impacts cannot be characterized to the product (Brander and Hutchison, 2009). However, since tallow currently has known and established market applications, it is considered to be used. The transport and rendering stages must therefore not be ascribed to the tallow.

There are currently three main market applications for tallow in the US: animal feed, methyl ester and fatty acids for different industrial uses (U.S. Census Bureau, 2008). However, because tallow is a constrained resource, it would divert its current market application to bioenergy applications, which would reduce its availability for current users, who will have to find substitutions.

Over the years, the market applications of tallow have changed. In 1992, feed dominated at 64%, followed by fatty acid at 22% and soaps at 11%. In 2000, feed gained the market with 75%, and soap fell to only 4% (Groschen, 2002). However, in 2007, fatty acid had 21% of the market, feed had 22% , and the new use for methyl ester had already gained popularity with 47% (U.S. Census Bureau, 2008). However, due to a lack of data on the tallow market and the fact that the figures did not seem to follow a particular trend, it was impossible to determine with certainty which application would be affected (Brander and Hutchison, 2009). Thus, all three were assessed. In different studies, the indirect impacts of tallow use varied according to the specific country for which the biodiesel demand was made, seeing as the market applications for the different regions were different (Grant et al., 2008). The calculations of the different scenarios are presented in Appendix III.

Animal feed

In this case, the characteristics of tallow had to be determined, and it was established that the tallow has very low protein content. Therefore, its use in animal feed is for energy purposes only. Consequently, the diversion of tallow for bioenergy purposes would create a loss of availability in energy fodder on the market. The affected—or marginal—energy fodder is wheat, and its production would increase to compensate. Wheat growing may also produce wheat straw. However, since it does not have any specific market applications and does not displace any land-grown products, it is not taken into account in this study (Bauen et al., 2010). In conclusion, if the affected tallow application was animal feed, then the result would be additional wheat production. Consequently, it is important to account for the land use change impacts of this extra wheat production and follow the same methodology as previously described. Also, in order to figure the substitutability between wheat and tallow with regards to energy content, their metabolizable energy contents were assessed.

For the purpose of this study, biodiesel production in the United States was considered to use inedible tallow that would otherwise be used for animal feed applications. This hypothesis was put forward for the following reasons. Firstly, scientists maintain that infected animal feed is the primary source of bovine spongiform encephalopathy (BSE), also known as mad cow disease.

Indeed, US officials believe that feed ingredient regulation is the most effective method of reducing BSE risks. In fact, since the widespread outbreaks in 1997, there has been a ban on feeding most mammalian proteins to cattle and other ruminants. However, prohibited proteins may still be fed to other animal such as pigs, poultry and pets. American government regulatory actions and industry practices therefore evolved to address food safety issues and options for using inedible oils and fats in the food industry may become more limited (Becker, 2004). Additionally, the consumption of inedible tallow and greases in the US in 2007 fell -7.6% yr/yr, of which virtually all went to animal feed (Commodity Research Bureau, 2008). It can therefore be assumed that the use of a constrained source of inedible tallow will result in a loss of availability of the feedstock for animal feed. Consequently, the deviation of the methyl ester and fatty acid applications is only considered in the sensitivity analyses.

Fatty acid applications

Tallow is used for its fatty acid content for cosmetics, rubbers, paints, synthetic surfactants, etc. The fatty acid source affected by the additional demand for tallow had to be the most competitive fatty acid source on the market and possess properties similar to tallow. Palm oil was the most likely replacement due to its market competitiveness and similar properties in terms of acid, iodine and saponification values and, essentially, its fatty acid content (Groschen, 2002; Shuangma Chemical Co., 2008). Consequently, the diversion of tallow from its fatty acid applications results in the increased production of palm oil. The methodology used to perform the system expansion and assess the relative LUC are addressed in this section.

Methyl ester

In this case, the goal was to determine if another vegetable oil or fat could take the place of methyl ester for biodiesel applications. This is a complex scenario because, in order to produce the biodiesel required for electricity generation, the use of tallow for biodiesel must be diverted to tallow for biodiesel used in electricity generation. This may seem counter-intuitive, but is explained as follows. The American government pushes incentives and targets to achieve a certain amount of biodiesel for the transportation sector. If there is ever a lack of feedstock to produce the said amount, then the feedstock will have to come from other sources, mainly the marginal oil on the market. This again leads to the use of palm oil to make up the loss in tallow availability.

2.4.2.4 Biogas from municipal organic waste (Italy)

In Italy, there are currently several MSW disposal options. In total, 25% of the waste is usually incinerated, 50% is landfilled, 12% is sent to a waste-to-energy facility or to a mechanical biological treatment facility, and marginal amounts are processed by composting facilities. In order to figure out which type of MSW disposal would be avoided, all options were assessed. Indeed, it was important that the disposal centers have sufficient amounts of MSW entering the unit to produce the significant amount of biogas needed to operate the turbine. The assessment of the information gathered from (APAT, 2006) led to the conclusion that composting facilities could not provide the necessary amounts of waste. Additionally, the landfilling systems that would be substituted are the ones that do not already produce biogas or other co-products or provide other services (i.e. mechanical biological treatment centers (MBT) and some types of landfills) or produce electricity from the waste (i.e. incineration) (Arena et al., 2003). This is such because the products are used for a service that cannot be diverted to this application. It would be impossible to disrupt the management of these facilities. Finally, only landfills that are not currently generating biogas constitute the avoided waste management system. A sorting plant facility is necessary in order to have the adequate organic matter for biogas production. The plant collects the MSW and separates the organic fraction for the anaerobic process from ferrous materials that might be reused and from discarded MSW sent to the landfill.

Biogas production generates solid and liquid digestates. The use of these digestates in agricultural practices leads to positive indirect impacts. Indeed, the digestates can be used as fertilizers, thus avoiding the production of N, P_2O_5, K_2O fertilizers. Also, the application of organic matter from the solid digestate reduces CO_2 emissions since it increases their humus intake, transferring C to the soil sink. Also, peat production could be avoided since its use for soil structure would be unnecessary (Schleiss, 2008).

Because the use of the organic fraction of MSW avoids a quantity of MSW to be landfilled, these avoided impacts are credited. Indeed, air and soil (leaching) emissions and land occupation effects are avoided. In the case in which there is an avoided use of land management system for an amount of MSW, the fraction that is not landfilled is credited. In the cases in which there is an avoided production (fertilizers, ferrous materials, peat, etc.) the impacts are credited to the biogas system.

2.4.2.5 Biogas from manure (Germany)

The anaerobic process for biogas production is a multi-output process with two products: digested manure (currently used as a fertilizer) and biogas. However, in conventional farming, manure is still produced and constitutes a waste product of animal husbandry. Hence, all manure production impacts are allocated to animal husbandry since it is not the determining co-product. The same applies for the further use of digested matter. Consequently, a system expansion is not necessary, and the only impact taken into account is the difference in fertilizer quality between the undigested (conventional) and digested manure. This is due to the fact that there are changes in emissions from the handling and storage of raw materials and digestates (i.e. the storage of liquid manure leads to spontaneous methane and ammonia emissions that decrease when manure digestion and the recovery of the biogas that is produced replace conventional manure storage systems (Berglund and Borjesson, 2006)).

As mentioned, the impact of manure spreading was not taken into account here, since the fertilizing would occur even if there was no biogas production. Thus, the production of biogas should not generate an extra environmental burden. The only fertilizing impact that is taken into account is the difference in NH_3 emissions and the change in nutrient leaching from fertilizing with digested versus undigested manure (Berglund and Borjesson, 2006).

2.4.3 Approach to land use change (direct and indirect)

2.4.3.1 Sugarcane ethanol (Brazil)

Direct LUC

The carbon emissions related to direct land use change impacts were taken from work by (Bauen et al., 2010). Indeed, the study assessed all the possible market responses from the additional demand for sugarcane bioethanol. It was determined that the demand could only be met by increased sugarcane production, which could occur in two ways: above baseline yield increase or cultivated area expansion. In the case of direct LUC, the methodology consists in assessing historical land expansion trends and relating them to the specific carbon emission factors from the Winrock data (US.EPA, 2009) for each type of land conversion.

Indirect LUC

As previously mentioned, the market response was assessed. However, in the context of indirect LUC, the assessment was extended to account for how the global sugarcane market was affected. It was found that sugarcane could not be replaced by other products such as sugar beet or corn syrup and that only additional sugarcane production could take place but not necessarily in Brazil, since the markets in the US, Thailand, China, the Philippines, Central America and the Caribbean, and South America are affected as well. Finally, since there were many different scenarios assessed, the average of the factors found was used as the factor in this study. The higher and lower value factors were used in sensitivity analyses.

2.4.3.2 Biodiesel from palm oil (Indonesia)

As previously stated, palm oil produces co-products. Therefore, the additional palm oil demand does not only entail an added demand for palm oil but also an additional supply in palm kernel expeller and palm kernel oil. The palm oil demand is met by an increase in plantation areas—mainly in Indonesia—and the added palm kernel meal avoids the expansion of areas for soybean and wheat production (as in the previous section) in different countries. The factors found in (Bauen et al., 2010) were adapted based on the assumptions that were made earlier when performing the system expansion. Indeed, Bauen et al. considered that the PKO would displace coconut oil, leading to significant avoided coco expansions. However, coconut oil is considered constrained in (Schmidt and Weidema, 2008) because it is a small-holders crop, takes 5-7 years to attain maturity and does not have the same market applications. Thus, it was assumed that, instead of the causing the displacement of coconut oil, it simply avoids a fraction of palm oil production and its relative land expansion impacts. In the case of avoided expansion, the Winrock emissions reversion dataset (i.e. the amount, type of land reverting to other different categories of land) was used as factors. The calculations relative to the modifications of the original carbon emission factors and those actually used are presented in Appendix IV.

2.4.4 Methodology for electricity substitution

Two approaches were considered to determine the type of electricity that would be substituted by a gas turbine running on alternative fuel. The first involves identifying the long-term marginal technology (i.e. the technology installed due to expected long-term changes in demand). This approach is considered to be the state-of-the-art methodology in consequential LCA. However, many studies have found that determining only one long-term marginal technology is often unwise in light of the uncertainty in the method.

The second approach consists in determining the short-term marginal technology (i.e. the existing technology whose output would change due to small changes in demand or the type of electricity source that would be substituted if the power plants were in operation) by looking at the marginal costs (i.e. fuel costs) of the production of an extra MJ of electricity and identifying the types of electricity (with similar production costs). The former would potentially be displaced by the turbine running on alternative fuels.

2.4.4.1 Long-term affected technology

In order to determine the affected energy source, the approach described in the literature review by (Weidema, 2003) was used. The assessment looked at the constraint criteria on the different technologies and the projected investments in the electricity market for all regions. Additionally, as other authors (Mathiesen et al., 2009; Curran, et al., 2005) suggested and concluded, more than one potential energy source was identified and the gas turbine properties were taken into account. Indeed, the identified technology must have a similar load following ability as the gas turbine, which played an important role in the identification process. The following points detail the results of the applied methodology:

1. Identify the scale and time horizon of the studied changes: Long-term due to the service life (20-25 years) of the power plants.

2. Identify the affected market: The electricity markets of the assessed regions.

3. Identify the market trend: There is a projected increasing demand for electricity in 2020 for all regions assessed (EIA, 2010b) (APEC, 2006), except for Germany, where a small decline in electricity demand is projected (IEA, 2007).

4. Identify the production constraints: The main constraint in this case is that the energy source must be able to adjust to the load, like the gas turbine does. Therefore, the must-run technologies (solar, wind, etc.) would not compete with the gas turbines (IEA and NEA, 2010).

a) The operation of CHP is not driven by electricity demand but rather by heat demand (Mathiesen et al., 2009).
b) The wind power plants are dependent on wind speed and solar plants on sunshine (Mathiesen et al., 2009).
c) Hydroelectricity is constrained by the geographic context of the country, and the decision is based on policy and politics. The installation of a gas turbine would therefore not affect the construction of a hydropower plant (Weidema et al., 1999).
d) Nuclear power plants run on base load and cannot start up or shut down like gas turbines (IEA and NEA, 2010).

5. Identify the suppliers/technologies most sensitive to changes (affected technologies that are the most or least competitive): The rationales for the identification of the long-term affected technologies in the different regions are detailed in **Error! Reference source not found.** 2.4. hen more than one affected energy source could be identified, the primary affected technology was used in the base case while the second was used in the sensitivity analysis.

Table 2.4: Identified long-term affected energy source

Region	**Affected energy source**	**Rationale**
BR	**NG**	According to the projections for future investments in new energy sources for the country, Brazil's heavy dependence on hydropower, which accounted for 83% of electricity production in 2002, is likely to be reduced in the future to the benefit of natural gas (IEA, 2004). If the

		gas market grows, gas-fired electricity generation could reach 22% of the total energy production in 2030. Brazil's primary energy demand is expected to grow at an average annual rate of 2.1% in the 2004-2030 period, resulting with 349 Mtoe in 2030. In the same project period, natural gas increases rapidly at an annual rate of 3.8%. The next highest annual growths are nuclear at 2.9% (but only from 2004 to 2015) and hydropower at 2.3%. However, as previously stated, nuclear and hydropower may not be considered as technologies affected by the turbine because of the incompatibility in their characteristics and different constraints. On the other hand, coal demand only increases 0.9% per year, and its share falls from 7% to 4% in 2030 (IEA, 2006). Consequently, the only significant and valid type of energy source that may be affected in the long-term is natural gas.
CN	**1.Coal** **2.NG**	According to prominent sources, the most important investments will be in coal power plants for 2030. However, the energy sources near big cities would be natural gas, where emission targets are necessary to reduce air pollution (EIA, 2010b); (APEC, 2006). Since the specific location of the turbine is not known, it cannot be determined for certain which type would be affected. Indeed, the added electricity generation from 2007 to 2030 comes from coal (72%), hydropower (10%) and nuclear energy (8%). Finally, natural gas accounts for 4% and actually decreases for oil based generation. It may be mentioned that gas and coal fired technologies using carbon capture and storage (CCS) account for almost 10% of the additional capacity in 2002-2030 (IEA, 2009b). In light of these projections, coal was identified as the primary type of energy source affected, with natural gas coming in second. Coal will therefore be used in the sensitivity analysis.

DE	**Coal**	According to the IEA's 2007 projections, in order to match declining demand in electricity from 2010 to 2030, total electricity generation should fall by an average annual rate of 0.3%, reflecting decreases in electricity produced from coal, oil and nuclear and increases in all other fuels (IEA, 2007). Since electricity demand in Germany is expected to decline, the method to determine the affected technology must change. Indeed, it is no longer the most competitive technology that is affected but rather the least competitive technology. Indeed, the most competitive energy sources would be those that increase the highest within the projection period, whereas the least competitive are either the ones that decrease in capacity (at a higher pace than what can be covered by the decrease from the regular, planned phasing out of capital equipment) or that stay put (decreasing at a rate less than the average replacement rate for the capital equipment) (Weidema, 2003). While assessing Germany's projections, it can be noted that the net change in electricity output from 2010 to 2030 is -33GWh, where the most significant increases for some energy sources are natural gas (94GWh) and solar, wind etc. with 53GWh. However, the most significant decreases are nuclear (-130.1 GWh), coal (-61GWh) and oil (-0.6 GWh) (IEA, 2007). Consequently, the capacity that would not be installed in favour of gas turbines running on alternative fuels would be coal since it is the energy –source with the right characteristics that decreases the most in the projection period. New coal capacities will be installed (for 2016, there is 44500 MW of new capacity with hard coal accounting for a fraction). However, these capacities only account as capacities equalling the replacement rates of older coal plants (IEA, 2007). Therefore, the least competitive energy source (i.e. affected technology) is coal.
ID	**1.Coal** **2.NG**	In Indonesia, total installed power capacity is projected to increase almost threefold from 35GW in 2007 to 101 GW in 2030. According to

		the (IEA, 2009b), coal demand mainly driven by power generation and industry will grow at a rate of 4.2% per year—the fastest growing fossil fuel. By 2030, coal's share of primary demand reaches 29% to become the leading fuel in the energy mix, and its dominance in the electricity generation mix rises further from 45% in 2007 to 63% in 2030. By 2030, coal makes up 45% of the total capacity, while 31% is gas-fired. On the other hand, gas demand grows at a rate of 3.8% per year and accounts for over one-quarter of industrial energy demand in 2030. The largest gas users in Indonesia are power plants. Electricity generation from gas grows at 5.9% per year, and the share of gas fired generation increases from 16% in 2007 to 18% in 2030. Another study by the APEC confirms these trends, stating that the new capacity requirements for electricity generation to meet 2030's demands will be based on coal power plants (54%) and natural gas plants (40%) (APEC, 2006). Therefore, coal is the primary affected technology, while natural gas is the second and will thus be used in the sensitivity analysis.
IT	**1.NG 2.Coal**	Italy already has a high share of natural gas in its grid mix (42%) and is anticipated to continue investing in natural gas markets (EIA, 2010b). The IEA's 2009 energy policies review stated that, in Italy, the generation mix is likely to change in the coming years as plans to convert coal- and oil-fired power stations to alternative fuels including cleaner coal fired plants emerge. The authors added that an additional 7 GWE of gas fired capacity is currently under construction while another 5GW is either authorized or planned. Electricity generation from natural gas is expected to increase 85TWh from 2007 to 2030, while electricity generation from coal will increase by 25 TWh in the same time period. Consequently, of the additional electricity generated in 2007-2030, approximately 61% will be gas-fired and 18% will be coal-fired, with the remaining 20% coming primarily from nuclear and wind power (IEA, 2009a). Additionally, it was noted that over the last 10 years, the

		energy source with the greatest expansion has been natural gas plants (IEA, 2010). Coal-fired plants are expected to increase by 2030 but may become less popular and make way for natural gas power plants due to possible emissions targets and carbon taxes (EIA, 2010b). The European Union will see a pronounced general increase in natural gas and renewables.
US	**NG**	Natural-gas-fired plants account for 60% of 2010-2035 capacity additions, as compared to 25% for renewable, 9% for coal-fired plants and 3% for nuclear (EIA, 2011a). In the past years, many gas-fired power plants were opened, and, in 2030 it is expected that their share will be 25% of the grid mix. To cover long-term demands, coal power plants would still be needed, but their share in 2030 will actually decrease from their current share in the grid mix. Indeed, escalating construction costs have the largest impact on more capital-intensive generation technologies, including renewable, coal, and nuclear. However, federal tax incentives, state energy programs and rising fossil fuel prices increase the competitiveness of renewable and nuclear capacity (EIA, 2010a). Consequently, considering the significant difference in capacity addition percentage coming from gas- and coal-fired technologies, the technology that would receive the most significant investments is natural gas power plants (IEA, 2004).

2.4.4.2 Short-term affected technology

The short-term marginal technology is the existing technology whose output will change due to small changes in demand. In order to determine the affected energy source, it is necessary to identify the one that has the same marginal costs as the assessed gas turbine running on the relative alternative fuel. The marginal costs are the costs to produce an additional unit of electricity, which can be estimated to be the fuel costs (i.e. a combination of the cost of the fuel and the efficiency of the plant). For further clarification on this methodology, see Amor et al., previously discussed in the literature review.

The approach aimed to compare the fuel costs for 1MJ of electricity for each country. The types of electricity sources compared for each country were coal, oil and natural gas, since the fuel costs of the other energy sources were too low to be compared to those of alternative fuels (EIA, 2011b). The fuel costs were found in several data sources and always related to projected costs in 2020. In certain cases, when the projected costs could not be found, approximations were used. Since there were discrepancies in the fuel cost data, an average was used. To assess the uncertainty, higher and lower values were used in the sensitivity analysis. The fuel costs and the graph used to determine the affected technologies are presented in Figure 2-2: Fuel production costs for electricity generation in 2020. Another important factor that was taken into account and used in the sensitivity analysis was the impact of country-specific incentives on alternative fuel costs.

2.4.5 Sensitivity analyses

Many sensitivity analyses were carried out as part of this project to test the different assumptions in each assessed system and may be divided into three categories: those pertaining to alternative fuel production assumptions, those pertaining to electricity substitution and those pertaining to gas turbine operation. The following chapter discusses the results in detail.

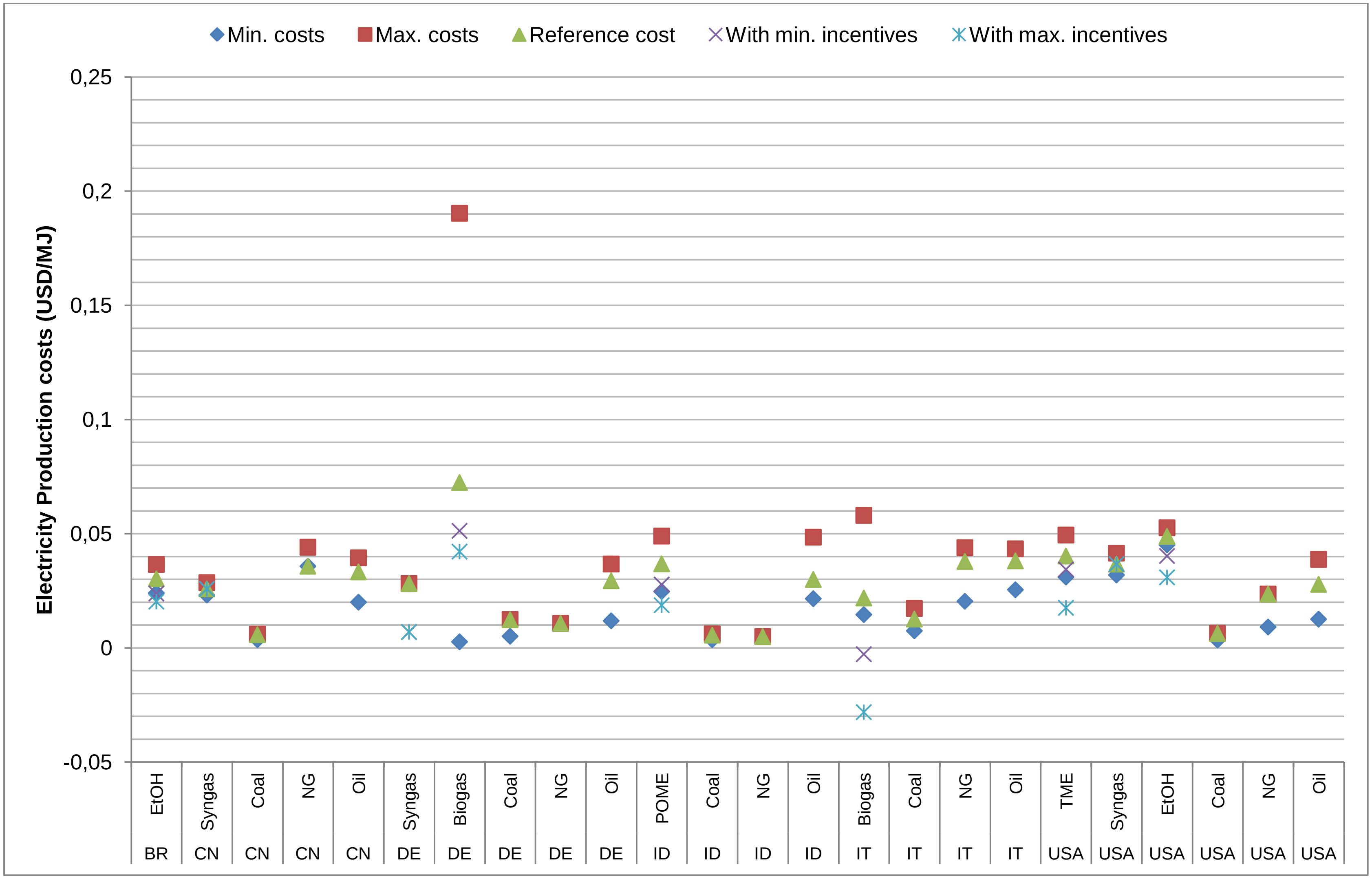


Figure 2-2: Fuel production costs for electricity generation in 2020

CHAPTER 3 RESULTS

This chapter discusses the CLCA results for all the different fuels and country scenarios in keeping with the objectives stated earlier. First, the results for the base cases (the nine fuels only) are presented. Secondly, the results from the many sensitivity analyses performed are summarized. Thirdly the results are shown for the ReCiPe impact method.

3.1 Results from alternative fuel supply potential assessment

This section covers national and international bioenergy production targets and policies, production costs for different alternative fuels, the state of the technology in each region and potential feedstock supply. The results are presented by type of feedstock category considered for fuel production. See Appendix VI for the results.

3.2 Results for the base scenarios

In order to correctly interpret the results in the figures, the impact results were divided into three (greatest contributor) life cycle stages: fuel production, gas turbine operation (i.e. power plant infrastructures and combustion emissions) and the impact credit from substituted electricity. Additionally, the net impacts are shown on the graph, which was used to interpret the results. In some cases, the net impact resulted in avoided impacts meaning that, while impacts are generated by fuel production or power plant operation, the impacts avoided either by co-products or electricity substitution are greater.

The general conclusions pertaining to the scenario with more or less potential environmental impacts are drawn from the base scenarios. However, when assumptions had to be tested to verify whether the conclusions from the base scenarios could be changed, sensitivity analyses were conducted, and their relative impacts on the results were presented in section 3.3**.** This was the case, for instance, for the different methods used to identify the substituted electricity, the market application affected by tallow use, the percentage of corn stover removal, etc. In all cases, the interpretation is based on the four IMPACT 2002+ endpoint categories. However, the interpretation method and derived conclusions may vary for each impact category.

To correctly interpret LCA results, they should be used as a tool for comparison, e.g. comparing one scenario to another, or one life cycle stage to another. Indeed, the results for each endpoint impacts should not be used in absolute values. Therefore, the results are most often translated in relative percentages.

Though the different sources of uncertainty are discussed in the next chapter, it is important to mention that a sizeable source of uncertainty in the impact results originates from the characterization method itself. Since this type of uncertainty cannot be verified in a statistical or sensitivity analysis, certain guidelines proposed by the authors of IMPACT 2002+ were followed to take the uncertainty into account (Humbert et al., 2009). These guidelines serve as thresholds of significance for the different impact categories. If these thresholds are not attained, no conclusions may be drawn as to which option has a better environmental performance. They are as follows:

1. -10% for climate change, non-renewable energy and mineral extraction (resource depletion)
2. -30% for respiratory effects from inorganic substances (human health), acidification, eutrophication
3. -One order of magnitude for toxicity and ecotoxicity effects

However, when the compared systems are considered to have similar inventories, the previous thresholds may be lower in order to formulate conclusions. Additionally, it was assessed that a difference of 30% is significant for the human health indicator, even when the systems are not correlated. Finally, the studied scenarios were measured to be considerably different, and the relative thresholds were used as a security factor to conclude that one scenario has a better environmental performance than the other.

3.2.1 Results from the base scenarios

The results were evaluated in absolute and relative terms in order to determine which scenario had a better environmental score. The impact results for each endpoint category are detailed in section 3.2.2. This first section presents the scenarios according to their ranking, from the best environmental score to the lowest. Table 3.1 gives the LCA results in a form that is suited to its use as a decision-making tool. Indeed, the partner is able to distinguish the scenarios that have generally lower environmental impacts from those with high environmental impacts and understand how the scenarios perform against one another for each end-point category. This is directly in line with the objective to determine the fuel and geographical context with the least environmental impacts. For some cases, the impact results between the scenarios did not sufficiently differ and did not exceed the necessary thresholds. In such cases, the scenarios were ranked the same.

The most dominant trends are that syngas from coal in the US and China have the worst environmental performances in all endpoint categories, followed closely by ethanol in Brazil and ethanol in the US. On the other hand, the most promising scenarios vary depending on the impact category that is taken into account. However, POME in Indonesia, followed by syngas and biogas in Germany, are always among the highest ranking scenario (with IMPACT 2002+).The other scenarios vary considerably in ranking depending on the type of impact assessed. The reasons as to why certain scenarios have either relatively high or low impacts toward the different endpoints are discussed in the next section.

Table 3.1: Base case scenario rankings

<table>
<tr><th>Ranking</th><th>1</th><th>2</th><th>3</th><th>4</th><th>5</th><th>6</th><th>7</th><th>8</th><th>9</th></tr>
<tr><td>Human health</td><td colspan="8">Syngas CN / TME USA/ Syngas USA /POME ID/ EtOH USA /Biogas IT /Biogas DE/Syngas DE</td><td>EtOH BR</td></tr>
<tr><td>Eco. quality</td><td colspan="2">POME ID/ Biogas IT</td><td colspan="2">Biogas DE/ Syngas DE</td><td colspan="3">TME USA/ Syngas USA/ Syngas CN/</td><td colspan="2">EtOH USA/ EtOH BR</td></tr>
<tr><td>Climate xhange</td><td>Syngas DE</td><td>POME ID</td><td>Biogas DE</td><td>TME USA</td><td>EtOH BR</td><td>Syngas CN</td><td colspan="2">EtOH USA/ Biogas IT</td><td>Syngas USA</td></tr>
<tr><td>Resource</td><td>POME</td><td>EtOH</td><td>Syngas</td><td>TME</td><td>Biogas</td><td>Biogas</td><td>EtOH</td><td>Syngas</td><td>Syngas</td></tr>
</table>

depletion	ID	BR	DE	USA	IT	DE	USA	USA	CN

To facilitate the interpretation of the results for decision makers, it may be necessary to normalize the results. Normalization aims to analyze the respective share of each impact based on the overall damage of the considered category. It facilitates interpretation by comparing the different impacts on a unit basis and in only one graph and is a preliminary step in the weighing operation. However, normalization was not carried out for this study for two reasons, which are explained below.

The normalization is performed by dividing the impact of an endpoint category by a normalization factor. Indeed, it is determined by the ratio of the impact per unit of emission divided by the total impact of all substances for a specific category, per person, per year. In the case of the IMPACT 2002+ method, the normalization factors are based on the impact of a European average from all the European emissions and extractions contributing to the considered impact category. However, this study compares product systems that are not only in Europe but also on other continents. The European normalization factors would therefore lose their relevance since they would be appropriate for some scenarios but very inadequate for others.

As mentioned earlier, an important reason why normalization is performed is to proceed with weighing. The weighing consists in giving a weight of importance to each impact category in order to get a unique score as a function of the relative importance of the different types of impacts. For the IMPACT 2002+ method, the weighing factors are left to the discretion of the practitioner. In this case, the partner showed more interest in seeing the tradeoffs (i.e. a more objective view of the results) than the results aggregated into unique scores. Finally, there is a probability that the use of the results by the partner may lead to a public study. However, according to the ISO 14044 standard, weighing may not be used for comparative assessments that are divulged to the public. Finally, the authors of the impact method suggest that the four endpoint categories be considered separately.

3.2.2 Impact results of the base scenarios of impact categories

The impact results for this section are presented in relative impact units. In some cases, midpoint categories detail the origin of certain impacts. In order to facilitate interpretation, for each impact category, the impacts are normalized to the scenario with the greatest impacts. Therefore, the scenario with the greatest impacts is used as a frame of reference and ascribed a 100% impact result, making it possible to reference the other scenario in terms of a percentage to a reference scenario.

3.2.2.1 Climate change

As shown in Figure 3-1, syngas in Germany and POME in Indonesia stand out as having significantly lower impacts. Indeed, compared to syngas from US, syngas from Germany shows a relative difference of -304% and -283% from POME. This may be partly explained by the fact that, for the base scenario, the substituted electricity is the long-term affected electricity which, in both cases, is coal. Coal power plants being a carbon intensive source of energy, their substitution becomes very beneficial to national environmental impacts. Electricity substitution impacts differ in Germany and Indonesia because their national average power plant efficiencies are different, with German plants being more efficient than the Indonesian ones. Their low contribution to climate change is further explained by the fact that no emissions derive from the combustion of these fuels (see section 2.3.4.3) and the low impacts of fuel production. Indeed, in the case of syngas from wood, no impacts are generated by the actual harvesting of the wood residues, and only the collection and transport of the residues are taken into account. Another scenario that shows low impacts due to fuel production is ethanol in Brazil. However, since, in this case, the substituted technologies are natural gas plants, which have higher efficiencies and a natural gas mix (specific to Brazil) that has lower impacts, the turbines post fewer benefits. Additionally, it is possible to conclude that syngas from coal in the US (100%) and biogas in Italy (-64%) have significantly higher impacts. This may be explained by the high combustion emissions. Also, the impacts of the production of syngas from coal differ significantly depending on whether the turbines are located in the US or China, mainly because of the type of electricity that is substituted and the use of electricity at the fuel production stage (the Chinese grid mix has a much higher fraction of coal than the American grid mix). Finally, for climate change impacts, the scenarios differ so significantly that it is impossible to deem one as the best.

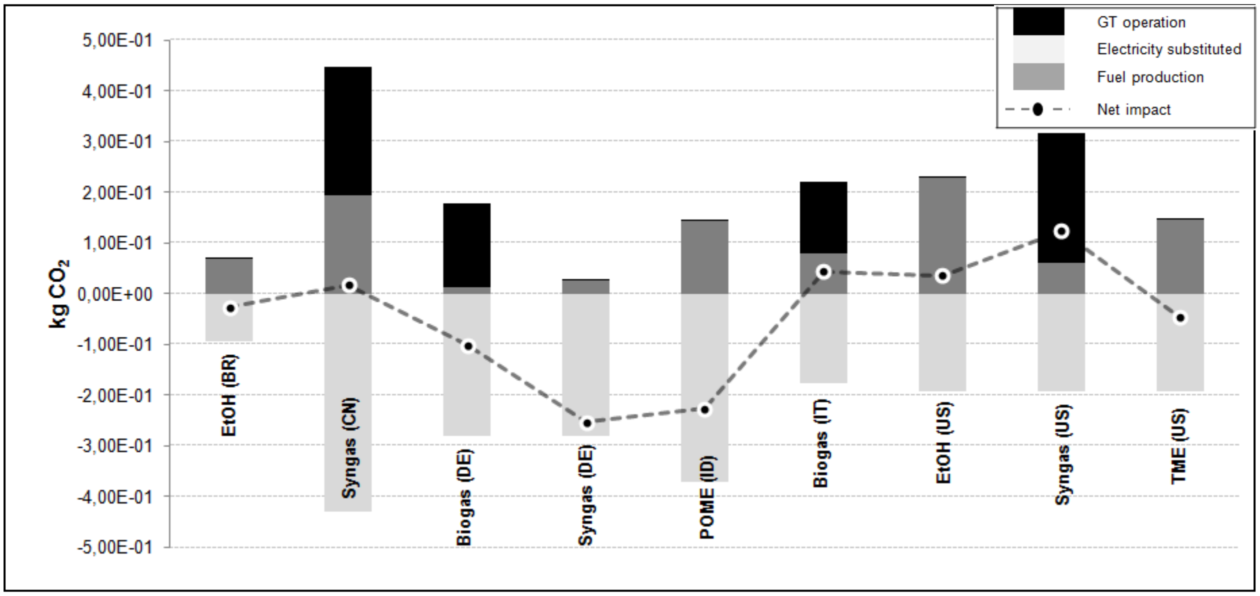


Figure 3-1: Climate change impact results for the base scenarios (IMPACT 2002+)

3.2.2.2 Human health

As presented in Figure 3-2, the ethanol from sugarcane is the only scenario that shows net impacts, while all the others have net credits, meaning that impacts are avoided for all the other scenarios. However, sugarcane ethanol does not only show net impacts but also significantly high impacts compared to the other scenarios in a scale of several orders of magnitude of difference. In relative errors, the other scenarios vary between -100% to -108%, as compared to Brazilian ethanol (100%). A closer look at the nature of the impacts shows that sugarcane cultivation is the major impact contributor, especially due to the use of arsenic as a pesticide and aldrin as a fertilizer in the cultivation process. It was assessed that 98% of the human health impacts stem from carcinogenic and non-carcinogenic human toxicity effects alone (Figure Figure 3-3). To illustrate this, Figure 3-4: Relative contribution to human toxicity shows the relative contribution of arsenic and aldrin to human toxicity impacts as compared to the total impact of the scenario. Finally, all other scenarios have the same order of magnitude and are considered to have similar impacts.

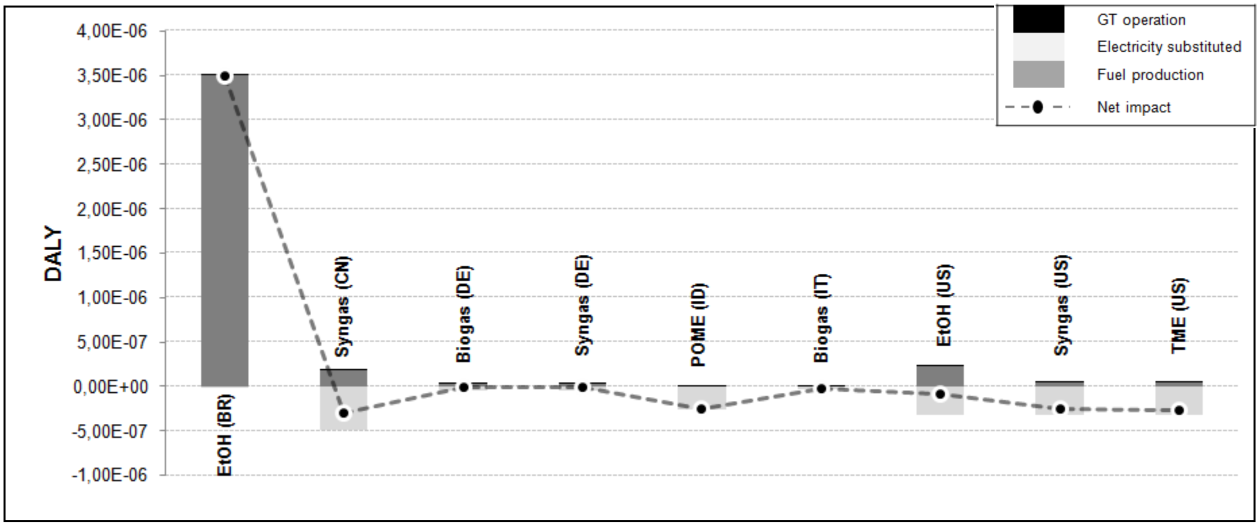


Figure 3-2: Human health impact results for the base scenarios (IMPACT 2002+)

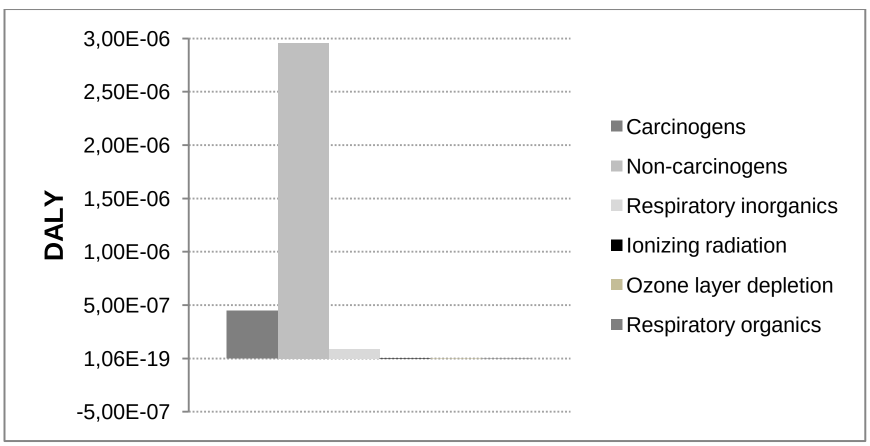


Figure 3-3: Contribution of different midpoint categories to human health damages for ethanol in Brazil

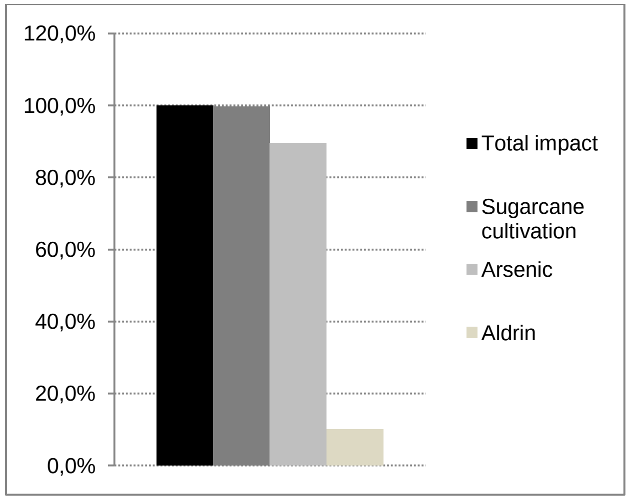


Figure 3-4: Relative contribution to human toxicity impacts for ethanol in Brazil

3.2.2.3 Resource depletion

Both scenarios that use syngas from coal in the turbine cause the most damages to resource depletion, with relative impacts of 100% for syngas from China and -62% for syngas from the US (Figure 3-5). These results are to be expected, since the main difference lies in the fuel production stage which, in this case, relies on coal as feedstock. Coal being a non-renewable fossil fuel, it greatly contributes to resource depletion. The scenarios that post the best environmental performances for this category by far are POME in Indonesia with -1120% (or 3.89·MJ in absolute error), ethanol in Brazil (-1020% or -3.54 MJ) and syngas from wood (-872% or -3.04 MJ). In the case of Indonesia, the high environmental performance is due to the impact credited for avoided synthetic glycerine production, which curbs 77% of the total impacts from fuel production. The major contributors to the glycerine impacts are mainly the use of propylene and chlorine in the preproduction stage. The ethanol scenario has lower impacts since ethanol production from sugarcane produces a surplus of electricity that may be sold to the grid. Furthermore, syngas from wood has lower impacts simply because the only major contributor is the fuel used to transport and collect forest residue, which is not substantial. Finally, as with the climate change damages, the scenarios differ considerably and it is impossible to deem one as the best.

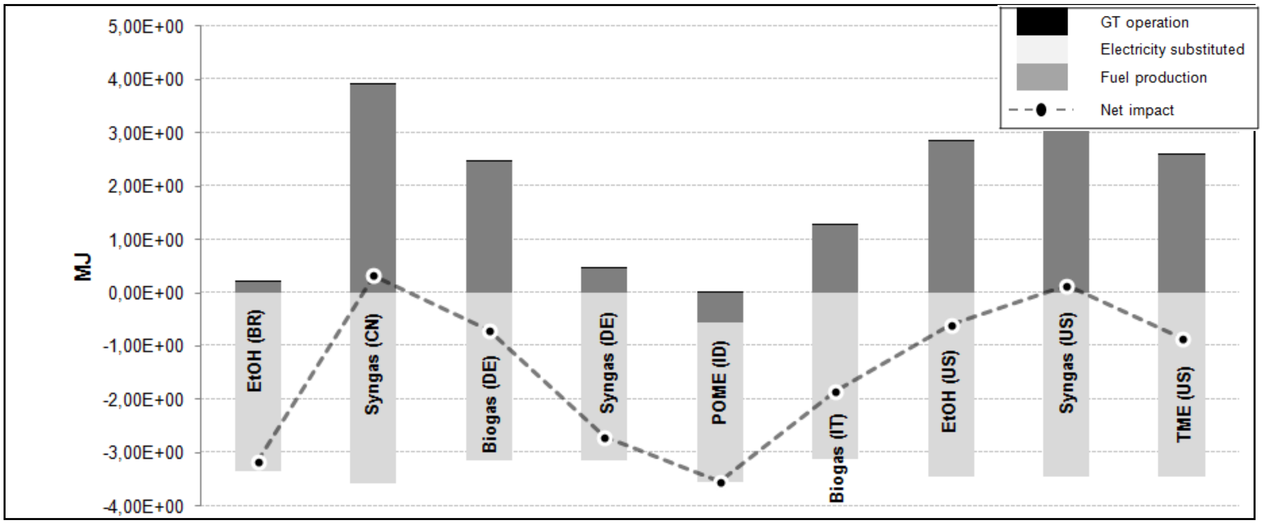


Figure 3-5: Resource depletion impact results for the base scenarios (IMPACT 2002+)

3.2.2.4 Ecosystem quality

According to the results (Figure 3-6), the scenario with significantly lower impacts is biogas from OFMSW in Italy (-102%). This is mainly due to the fact that the plant that sorts the organic fraction of municipal solid waste would recycle ferrous materials that greatly contribute to the avoided impacts. Indeed, ferrous materials show great impact in this category due to the aluminum and zinc emissions to the air that are harmful to the ecosystem and the significant use of water in the metal's production stage. Additionally, the anaerobic process avoids the production of fertilizers and peat, which avoids 57% of the impact of that process. Finally, the other inventory flows of the production stages are transport, natural gas production and the anaerobic process, which do not have high ecosystem impacts.

The scenarios with significant impacts are ethanol in Brazil (100%) and ethanol in the US (-48%). For the latter, the impacts are at 67% due to the additional corn production needed to compensate for the loss of soil fertility from stover removal. In fact, the biggest impact contribution to corn cultivation is land occupation. On the other hand, the Brazilian ethanol makes a much greater contribution to ecosystem damages due to sugarcane cultivation. Indeed, in this case, land occupation for cane culture contributes to 51% of the overall ecosystem damages, with aldrin and arsenic contributing 28% and 16%, respectively. It could be argued that the impacts of land occupation damages should be noted for palm oil in Indonesia. However, the type and area of occupied land yields lower impacts. Additionally, the production of palm oil indirectly avoids the production of wheat, which, in turn, avoids close to 55% of the total ecosystem quality damages of palm oil production. Also, the mineral fertilizers used to cultivate palm fruits contain heavy metals such as copper and zinc that are considered as heavy metal uptake because the outputs to the soil are higher than the inputs to the crops. This heavy metal uptake serves as soil nutrients and is a beneficial environmental service to ecosystem quality.

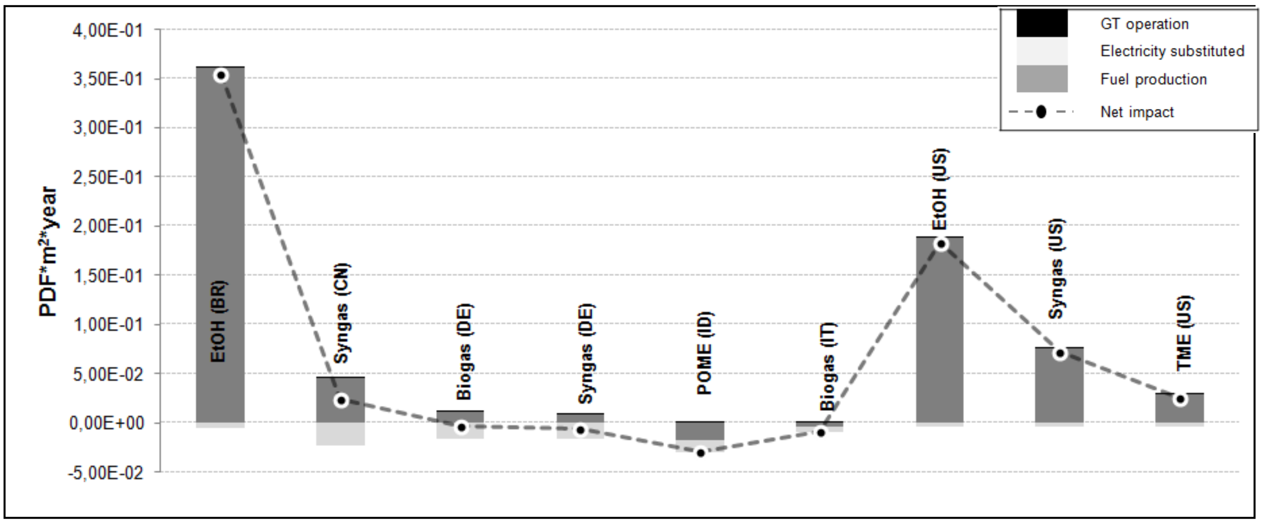


Figure 3-6: Ecosystem quality impact results for the base scenarios (IMPACT 2002+)

3.2.3 Contribution of life cycle stages

Generally, the stages that most contribute to avoided impacts or net impacts are fuel production and electricity substitution due to the fact that the CO_2 emissions from fuels that are derived from biomass are biogenic. Indeed, they are not considered to increase the atmospheric CO_2 concentrations since it is assumed that the emitted carbon is offset by the uptake of CO_2 resulting from the growth of biomass if it is sustainably sourced (US.EPA, 2009). As a result, CO_2 emissions from biomass-based fuel combustion are not included in the life cycle emissions impacts. However, this is not the case for syngas from coal or biogas from manure and OFMSW, where fuel combustion emissions play an important role in the net climate change impact. For syngas from coal, the fossil origin of coal results in permanent net additions of CO_2 in the air that would not have occurred if not for coal extraction and combustion. For both biogas scenarios and as previously mentioned, a significant amount of natural gas is fed into the turbines due to the insufficient amount of biogas generated by current large digesters. Consequently, the natural gas, coming from fossil sources, explains the contribution to climate change impacts during combustion.

3.2.4 Geographical relevance to impact contributions

As assessed and illustrated in the figures, the fuel production stage significantly contributes to the life cycle impacts of the different scenarios. An important contribution to the fuel production stage is feedstock production and its indirect impacts. This is illustrated in Figure 3-7, which presents the climate change contribution percentages of the feedstock (presented as either impacts or avoided impacts) on the fuel production stage. As the figure illustrates, the feedstock has important effects ranging from 190% to -660% of the fuel production impact. Since the type of feedstock depends on the geographical context, the impacts are clearly dependent on the geographical context. Another means of illustrating this is to compare the impacts of syngas from coal in the US and China, which are generally significantly different (section 3.2.2). Furthermore, as shown earlier, the identification of the type of substituted electricity has significant impacts on the life cycle impact and is dependent on the geographical context.

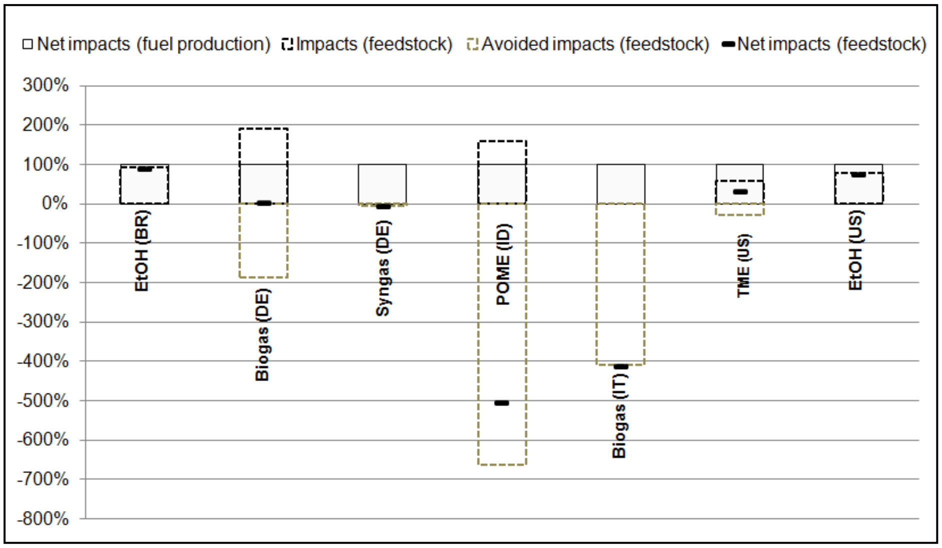


Figure 3-7: Contribution of feedstock impacts to the fuel production impacts for climate change

3.2.5 Impact on the environmental performance of the electricity sector

The interpretation of the results may lead to other interesting conclusions. Indeed, the study results do not only determine the fuels and geographical regions that have less potential impacts but also illustrate how the use of alternative fuels in the gas turbines would compare to the electricity that would be substituted by looking at the net impact and assessing whether it is positive or negative. A negative net impact shows that the use of the alternative fuel has lower impacts than its competing energy source, demonstrating that, from an environmental standpoint, the electricity market would benefit from these alternative scenarios. For the base scenarios, negative net impacts are shown for the resource depletion category. This is logical since the alternative fuel is replacing a non-renewable fossil fuel. The same benefits are seen for climate change but only when the alternative fuel is entirely from biomass. For human health, the benefit arises for every fuel except ethanol from sugarcane. Finally, in the case of ecosystem quality, the results vary greatly from one fuel to the next, and no conclusions may be drawn as to the fact that the electricity sector would lower its impact with these alternative fuels.

3.3 Sensitivity analyses

Based on the results presented in this chapter, it is important to corroborate the sensitivity of certain important parameters defined in the study in order to make sure they don't inverse the study's conclusions and quantify the impacts on the results in the cases in which they do. The sensitivity analyses are presented according to impacts on fuel production, gas turbine operation or electricity substitution stages.

3.3.1 Fuel production

The sensitivity analyses based on the different fuel production assumptions are presented in Table 3.5. In some cases, the impact result changed significantly, and the conclusion could even be reversed for some endpoint impact categories. The table presents the scenarios that were tested, describes any significant changes and the relative difference between the result and the base scenario, and clarifies when rankings are reversed. Practically all of the scenarios that were tested impacted the results. In some cases these impacts were insignificant, but, for some, the impacts were very significant. This was especially the case for biodiesel in the US, where, if the tallow used was originally intended for methyl ester or fatty acid applications instead of animal feed (base case), the impacts would be diminished by several orders of magnitude for ecosystem quality, climate change and resource depletion and enhanced by several orders of magnitude for human health. Finally, the table also indicates that the climate change impact category is the most sensitive to inventory changes, along with resource depletion and ecosystem quality when energy crops or wood cultivation are involved.

3.3.2 Gas turbine operation

It is important to substantiate the impacts of the turbines in combined cycle mode instead of simple cycle mode in order to assess the impacts of the implementation of alternative fuels on higher efficiency systems. This may prove significant if the partner chooses to run the turbine in combined cycle mode to meet new energy market needs and trends. Contrary to the sensitivity analysis in the fuel production section, the results were not compared to the base scenarios. Indeed, the scenarios were all compared to each other, and the new rankings were elaborated as such. Firstly, the net impacts of the different scenarios were assessed and are all lower than those of the base scenarios. This is logical since less fuel is produced and fewer emissions are generated per MJ of electricity. Additionally, looking at all the impact categories, only minor differences are noted in the ranking of the scenarios. The most significant differences are noted only for climate change. Indeed, in this case, POME from Indonesia is a better option than syngas from wood, and Brazilian ethanol, American biodiesel and Chinese syngas are now intertwined.

3.3.3 Electricity substitution

As previously mentioned, the affected type of electricity varies depending on the identification methodology. In this section, the results of using the short-term affected technology will be presented as along with the impacts of selecting the other long-term affected technology when more than one long-term technology was identified. These sensitivity analyses were important, since the results showed the significant contribution of electricity substitution to the net impacts.

3.3.3.1 Short-term affected technology

As previously explained, the short-term affected technology was identified using the fuel production costs for the different scenarios (Figure 2-2). By comparing the fuel production costs to the cost of the country's other energy sources, it is possible to determine the energy source that would be substituted. Electricity generation production costs were calculated based on different reference scenarios. Indeed, the reference cost is the average of the production costs found in the literature, with the minimum and maximum costs referring to the extremes found in literature. In the case of Brazil, fossil fuel prices in 2020 weren't known and the identification as based on American electricity costs. Another important factor that was taken into account was the incentive prices that would most likely be implemented in each country to promote biofuel production. Here again, when several incentives prices were found, minimal and maximal prices were applied to consider different potential realities in 2020.

3.3.3.1.1 Fuel production costs without incentives

The identified short-term affected energy sources (without incentives) are illustrated in Table 3.2. In this particular case, it is important to consider that some of these biofuels without any type of incentive may render the fuel non- competitive with any other energy source in 2020. This is the case for cellulosic ethanol in the US and biogas from manure in Germany. This would disable the competitive use of the turbine, and it was assumed that the turbine running on the fuels in those conditions would not operate. However, for biogas from manure, it should be mentioned that production costs varied greatly, and, in some cases, the fuel had very low costs. An average (i.e. reference costs) on which the identification was based was therefore taken into account. Finally, it was determined that the impacts on the results are insignificant and do not inverse the conclusions for all endpoints except climate change, for which certain changes in the rankings were noted. Table 3.4 illustrates the modified ranking for climate change from the best environmental performance to the worst.

Table 3.2: Identified short-term affected energy source (without incentives*)*

Region	**Alternative fuel**	**Short-term affected marginal technology**
Brazil	Bioethanol	Natural gas
China	Syngas	Oil
Germany	Syngas	Oil
	Biogas	Not competitive without incentives or feed-in tariffs
Indonesia	Biodiesel	Oil
Italy	Biogas	Natural gas
United States	Biodiesel	Oil
	Syngas	Oil
	Bioethanol	Not competitive without incentives or feed-in tariffs

3.3.3.1.2 Production costs with incentives

In this case, cellulosic ethanol from the US and biogas from Germany are competitive. Thus, the power plants would be installed and operated. However, the syngases from coal, being of fossil sources, would not be the target of incentives. The identified short-term technologies differ from the ones considered without incentives and are presented in Table 3.3. This being said, as with the previous sensitivity analysis, the impacts of the type of substituted electricity are most evident for climate change, insignificant for ecosystem quality and human health, and no reversed conclusions are seen for resource depletion. The new rankings are presented in Table 3-4.

Table 3.3: Identified short-term affected energy source (without incentives)

Region	**Alternative fuel**	**Short-term affected marginal technology**
Brazil	Bioethanol	Natural gas
Germany	Syngas	Coal
	Biogas	Coal
Indonesia	Biodiesel	Oil
Italy	Biogas	Coal
United States	Biodiesel	Natural gas
	Bioethanol	Oil

Table 3.4 : Scenario ranking for different types of affected energy source for climate change

	Ranking							
Scenario	1	2	3	4	5	6	7	8
Short term affected energy source without incentives	Syngas DE	EtOH BR	TME USA	POME ID	Biogas IT	EtOH USA	Syngas USA	
Short term affected energy source with incentives	Syngas DE	Biogas IT	POME ID	TME USA	Biogas DE	EtOH BR	EtOH USA	
Long term affected energy source	Syngas DE	POME ID	Biogas DE	TME USA	EtOH BR	Syngas CN	EtOH USA/ Biogas IT	Syngas USA

3.3.3.2 Other long-term affected technologies

This sensitivity analysis represents the base case, except for the scenarios that have other long-term marginal technologies that were identified. This was the case for China, where in big cities, natural gas would be used to avoid additional air pollution. This highlights the importance of the location of the turbines on the overall impacts. This was again the case for biodiesel from Indonesia, since 54% of the new capacity requirements for electricity generation are predicted to be coal, while 40% are predicted to be natural gas. Hence, since coal is the cheapest electricity source, it was used as the base case. However, natural gas had to be tested as well. Also, natural gas and coal had to be tested for European countries, since the literature specifies that both types of energy sources are marginal. The results of this sensitivity analysis are presented for each scenario in Table 3.5.

3.3.4 ReCiPe impact characterization method

As mentioned earlier, the characterization method impacts the results due to the uncertainties related to its characterization modeling. In order to test the sensitivity of the choice of impact method, it is important to test the studied product systems with a different method. In this case, the authors used the ReCiPe method, which was released in 2009 and has midpoint categories and only three endpoint categories: ecosystem quality (species*year), resource depletion ($) and human heath (DALY). Subsequently, when compared to IMPACT 2002+, the same conclusions were drawn for resource depletion. However, the ReCiPe method models climate change impacts differently, placing them further in the cause and effect chain and separating them into damages to the ecosystem and human health. This explains why the Brazilian ethanol category does not spike as much as with IMPACT 2002+ for the human health category, since ethanol did not have particularly high climate change impacts. As for the other scenarios, the syngases from coal are still the most impacting alternatives, and Indonesian biodiesel and German syngas remain the most environmentally favourable scenarios. Finally, the most important conclusions that can be drawn from this sensitivity analysis pertain to the ecosystem quality endpoint category. Indeed, contrary to the conclusions for every endpoint category, POME has become one of the most significant contributors. In fact, three scenarios that either directly or indirectly use energy crops have the most significant impacts (i.e. ethanol from in US and Brazil and POME in Indonesia). Indeed, unlike IMPACT 2002+, ReCiPe models the ecosystem impacts due to land transformation. In the case of corn stover ethanol, the impacts are present since there is an increase in production of corn to compensate for the loss in soil fertility. Additionally, corn has often been showed to an energy crop that impacts climate change and ecosystem quality. The differences are shown in Figure 3-8.

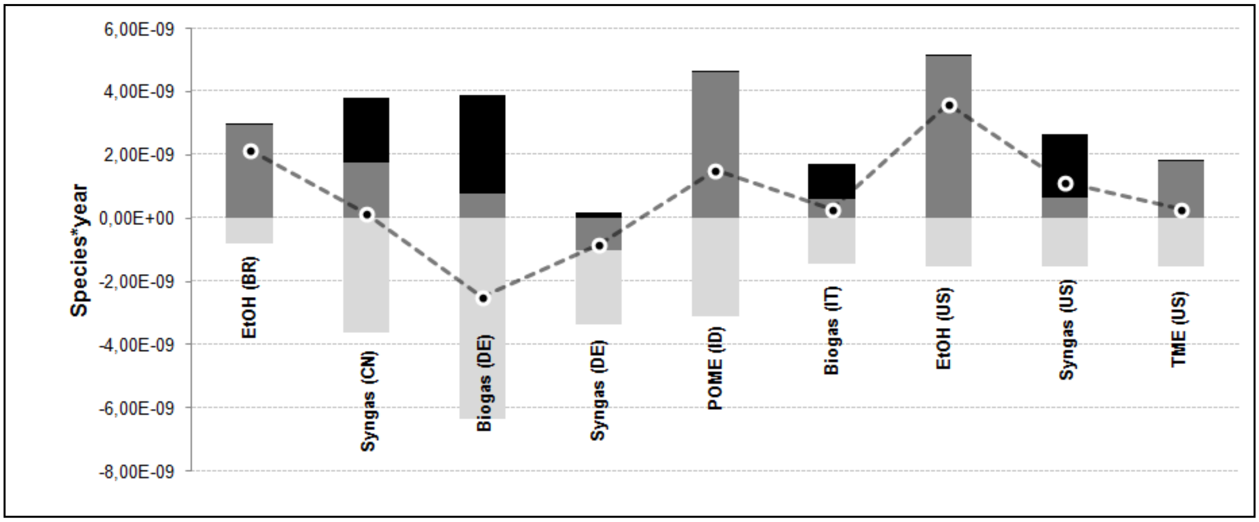


Figure 3-8: Ecosystem quality impacts (ReCiPe)

Table 3.5: Summary of conclusions from the sensitivity analysis

Country	Fuel	Definition of the scenario	Significant changes	Nature of change	Category of impact	Changes compared to base scenario (%)	Inversed conclusions
BRAZIL	EtOH	Lowest land use factor	Yes	Decrease	CC	-89%	Yes, now has the same impacts as TME from US
		Highest land use factor	No	Increase	CC	89%	No
CHNA	SYNGAS	If there is no slag sale, then there is no slag production and disposal credit.	No				No
		If there is no sulphur sale, then there is no sulphur production and disposal credit.	No				No
		The other long-term electricity identified: natural gas in cities (because of air pollutants)	Yes	1) Increase 2) Decrease	1) CC 2) RD	1)1820% 2)90%	1-Yes, it is now the most impacting scenario 2-No

INDONESIA	POME	Lowest land use factor	Yes	Decrease	CC	64%	Yes, now has less impacts than syngas DE
		Highest land use factor	Yes	Increase	CC	81%	Yes, now has more impacts than TME and biogas DE
		Other long-term electricity identified: natural gas	Yes	Increase	CC	71%	Yes, now has more impact than biogas from Italy and Germany
GERMANY	SYNGAS	High-added timber product	Yes	Increase	EQ	205%	Yes, now has more impacts than biogas from manure and OFMSW
		Low-added timber product	Yes	Decrease	EQ	12%	No
		With 70% of avoided forest residue burning (70%).	No	Decrease	CC	2%	No
USA	TME	Methyl ester as affected application of tallow	Yes	1, 2, 3) Decrease 4) Increase	1) CC 2) RD 3) EQ 4) HH	1) 6000% 2) 9000% 3) 197000% 4) 3000%	Yes, the scenario is by many orders of magnitude either the least or, in the case of HH, the most contributing scenario.

		Fatty acid as affected application of tallow	Yes	1, 2, 3) Decrease 4) Increase	1) CC 2) RD 3) EQ 4) HH	1) 65000% 2) 95000% 3) 2018000% 4) 36000%	Yes, the scenario is by many orders of magnitude either the least or, in the case of HH, the most contributing scenario.
	EtOH	If 100% corn stover removal (fertilizer use is the same since it has to be doubled but on half the land, there is an additional corn production since note a sustainable removal, but transport and baling diminishes)	Yes	Increase	1) CC 2) EQ	1) 644% 2) 181%	1) Yes, now has more impact than biogas in IT and syngas in US 2) Yes, now is the scenario with the most impacts.
		Electricity surplus generated by ethanol production is not sold (i.e. no credit)	Yes	Increase	1) CC 2) RD	1) 101% 2) 109%	1) Yes, now has more impacts than biogas in IT 2) No
	SYNGAS	If there is no slag sale, then there is no slag production and disposal credit.	No				No

		If there is no sulphur sale, then there is no sulphur production and disposal credit.	No				No
		If gasification is not at the same site as the power plant, there is additional fuel transport.	No				No
ITALY	**BIOGAS**	The transport is modified; the sorting plant is at the power plant and not the landfill.	Yes	Increase	1) CC 2) RD	1) 94 % 2) 32%	1) Yes, now has more impact than EtOH in US 2) No
		The other long term electricity identified, which is coal.	Yes	Decrease	CC	281%	Yes, now has less impact than EtOH in BR, TME in USA and syngas in China

CHAPTER 4 DISCUSSION

This chapter is a general discussion on the content of the thesis. It first considers the consequential methodology used in the study and then goes on to discuss how the LCA impacts are dependent on the geographical context. This section also goes over the conclusions that could be drawn from the different sensitivity analyses and explores the different sources of uncertainty. Finally, the chapter links the results from the potential fuel market supply in 2020 and their environmental performance.

4.1 The consequential approach

The consequential approach that was used for this LCA consisted in performing system expansions for co-producing processes and assessing indirect impacts related to the use of constrained resources, land use change impacts and electricity substitution. The following sub-section discusses how the study dealt with these issues and how it might compare to what is normally seen in LCA studies.

4.1.1 Electricity substitution

In LCA studies, correct electricity substitution modeling is generally not a priority and a **single long-term affected technology** is chosen as a default value. However, in this case, the electricity substitution is such a major contributor to the impacts that there must be an additional focus on identifying the substituted electricity. Indeed, considering only the long-term perspective (i.e. change in capacity) did not allow for a complete assessment of the energy system's reaction to the injection of 1 MJ of electricity from the gas turbine into the grid. In fact, operational changes in existing plants are important in the short term. Moreover, taking the short-term approach into account has been shown to be more precise in determining operational change in existing plants, than relying on the long-term approach to identify change in future installed capacities.

Considering energy market interactions, one study showed that the average yearly marginal technology was a mix of coal and natural gas only (Lund et al., 2010). However, considering a combination of two marginal technologies is not in keeping with the consequential approach and was therefore not a possible approach in our study. Additionally, Weidema (1999) identified several possible marginal electricity sources (e.g. wind power plants). Mathiesen's (2009) literature review highlighted several studies that identified CHP, biomass and hydropower as marginal technologies. However, in these cases, the affected power plant was not impacted by gas turbine operation but only by a general change in electricity demand. This means that the results of this study are less damageable to the environment since fossil fuel plants, instead of renewable energy plants, are substituted.

The literature review demonstrated the importance of considering the specificities of gas turbines and only substituting the energy sources that have similar characteristics (Mathiesen et al., 2009). Moreover, the consequences of identifying more than one affected technology were evident in the results of the sensitivity analyses, which clearly indicated how considering a single affected plant could result in significant uncertainty (Mathiesen et al., 2009) in light of the many other plausible substitution scenarios and the difference in impact scores relative to each type of substituted electricity.

Finally, many different studies on electricity systems modeling were researched. They showed that the electricity market is very unstable and sensitive to the operational and capacity changes made by a particular country and surrounding nations. Ideally, given that a country's electricity production system is dynamic, this LCA study would have assessed the dynamic changes to the energy system, showing the marginal changes in time. The initial (i.e. short-term) responses would come from production adjustments alone before the production capacity can adapt to the perturbation. In time, the power system would finally reach equilibrium. Then, affected technologies could be identified along with their relative importance and the marginal long-term effects would be known. However, considering the different countries and fuels assessed in this study, the assessment process would have been extremely labour intensive and may have proven to be irrelevant since it was not the primary objective of the study.

4.1.2 Indirect impacts of constrained resources

The LCA studies on biofuels do not usually take into account the indirect impacts related to the use of feedstock from constrained resources. However, there is a diversion in the biofuels market toward this type of feedstock, favouring residues and waste streams to dedicated energy crops for either environmental or economical purposes (European Biofuels Technology Platform, 2011).

The importance of accounting for these indirect impacts was illustrated in the results from the base scenario and sensitivity analyses. Indeed, the results showed that the emissions and land occupation credits from the avoided landfilling significantly reduced the impacts of biogas from OFMSW. Additionally, the impact of corn stover removal on corn cultivation significantly affected ecosystem quality. More importantly, when diverting the tallow from methyl ester and fatty acid applications, the impacts were extremely significant. Consequently, considering these impacts in biofuel studies with waste or residues is crucial to a complete assessment of the possible environmental impacts and might show either additional benefits or harmful consequences.

The work carried out by the UK government for the Renewable Fuels Standard (Brander, et al., 2009) shows that UK tallow, similarly to US tallow, has many current uses (e.g. oleochemicals, soap, animal feed, biodiesel, heat). As in this study, it was not possible to establish the order in which existing tallow uses will switch from tallow as a result of increasing demand for biodiesel, and a range of weighted average indirect emissions were calculated. Assessing the carbon emissions related to the biodiesel production from tallow, the results from both studies are similar; 57gCO_2-eq/MJ versus 73 gCO_2-eq/MJ in our study. Additionally, the UK study assessed biogas from MSW and, not knowing the type of waste system that would be affected, used the same method. However, in our case and as previously mentioned, we used the consequential affected technology. No weighted average was used and the affected user had to be identified. Unlike the UK study, our assessment of MSW biogas production results in a positive net climate change impact. This may be explained by the fact that many processes such as MSW sorting, collection and, overall, different inventory processes and assumptions could have not be taken into account. However, the conclusion remains similar: the use of materials with existing uses is likely to create additional impacts that are not currently accounted for and, alternatively, the use of materials that are disposed of can lead to emissions reductions.

4.1.3 Land use change

LCAs and carbon footprint studies are becoming increasingly prevalent. If ILUC effects are not properly included in the LCA results, there is a great risk that the results will be misleading (Christiansen, 2011). This was demonstrated in this study, since considering the impacts of climate change due to ILUC significantly impacted the end point category. Indeed, when assessing the difference between using a low or high ILUC factor, significant changes were observed for both Brazilian ethanol and Indonesian biodiesel. Consequently, ignoring these impacts would noticeably change the results for energy crop based fuels and would therefore inadequately quantify their climate change impacts.

The US EPA study (2009) also assessed the corn stover and revealed very small effects on the acreage of other crops—the net impact being null. This was expected because experts considered that corn stover production does not displace other crop production, since corn stover is a residual product of corn cultivation. The Forest and Agricultural Sector Optimization Model (FASOM) projected minor amounts of crop shifting in the corn stover scenario because using corn stover for ethanol can increase the profitability of corn production in certain regions and lead to subsequent impacts. Unlike the American study, our study showed that the corn stover scenario generated greater climate change impacts than the sugarcane ethanol scenario. This is mainly due to the 2,4-Dichlorophenoxyacetic acid (2,4-D), a herbicide/pesticide used in corn cultivation, as well as the tillage. Since no impacts due to additional corn production were taken into account in the FASOM study, unlike our study, this explains the differences found between both studies' results.

The main difference between our LUC factors and those calculated by (Bauen et al., 2010) is that avoided coconut expansion is not considered. This is due to the fact that we used Shmidt and Weidema's (2008) assessment stating that the marginal vegetable oil would have to have the same properties as palm oil for its markets (e.g. frying oil/fat, margarine, shortening and salad oils and industrial oils) and that soy is a palm oil substitute while lauric oils (e.g. coconut oil) are not. This explains why the climate change impacts of palm oil biodiesel are approximately double those of sugarcane ethanol.

Finally, it should be noted that POME from Indonesia has low impacts even though the ILUC factors for climate change were considered and that this does not tally with what is usually seen in LCA studies on biofuels (Bauen et al., 2010). This can be explained by two different factors. First, the avoided production of wheat and soybean that arises from the additional production of palm oil provides a considerable credit to ecosystem quality impacts. This is the case because, like palm oil, the crops have considerable ecosystem impacts from land occupation. Second, the characterization method that was used (i.e. IMPACT 2002+) does not model the contribution of land transformation to ecosystem damages, which is typically considerable for palm oil cultivation. The latter will be discussed more thoroughly in section 4.3.

4.1.4 Importance of consequential modelling

As previously stated, this LCA used a consequential approach for impact modelling. Indeed, while assessing the direct and indirect impacts of the alternative fuel production, the importance of considering indirect land use changes, system expansion and indirect impacts from the use of constrained resources was unfolded. Figure 4-1 illustrates the importance of considering these effects for climate change. In several cases, considering these indirect impacts inverse the conclusion of the fuel production impacts, were they not to have been assessed. This illustrates how consequential LCA modelling renders significantly different results than those from an attributional LCA. Indeed, the latter would only consider the direct effects from the fuel production (i.e. direct physical flows) such as the plant infrastructures, and raw material and energy to produce the fuels. System expansion, in this assessment of climate change, showed avoided (i.e. credited) impacts in all cases, whereas, indirect land use change resulted in higher impacts to climate change. The indirect impacts from the use of constrained resources results either in positive or negative impacts depending on the feedstock used. In most cases however, considering the indirect impacts decreases the net impacts from the fuel production.

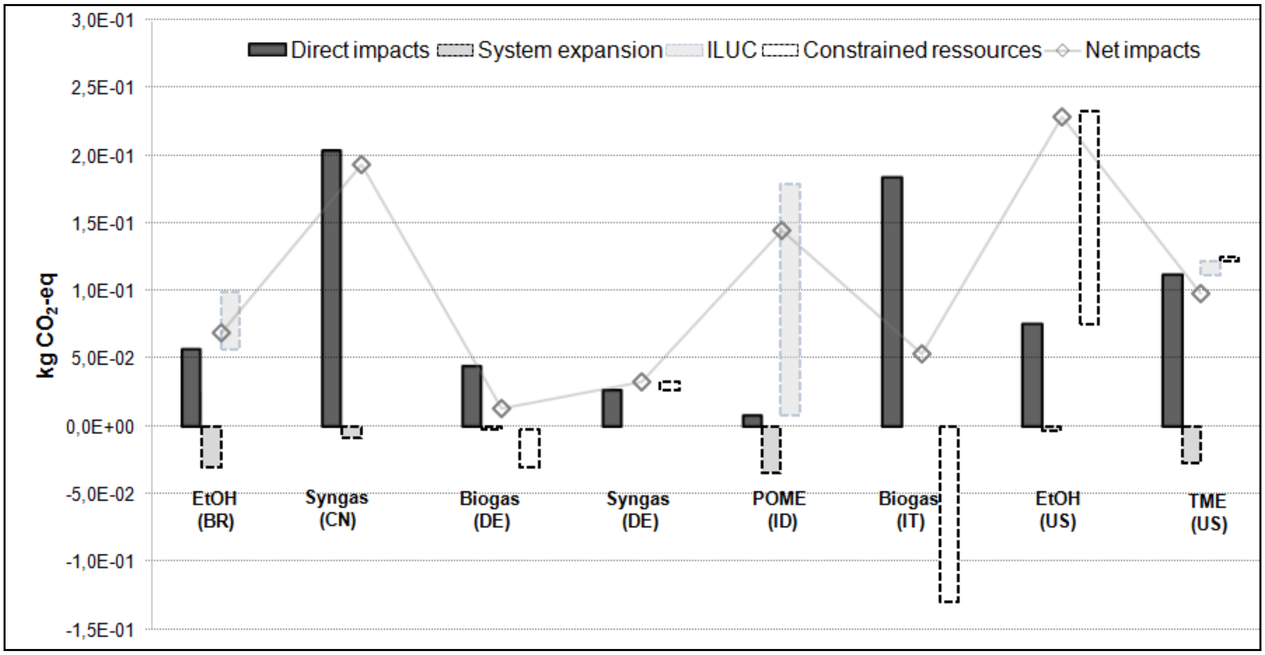


Figure 3-9 : Contribution of consequential modelling to fuel production impacts for climate change

4.2 Impacts dependent on geographical context

This project is characterized by the fact that it determines where the turbine should be located. Indeed, the study indicates how the impact of the electricity generation from the different fuels is specific to the geographical context in several ways. First, considering trade issues and technical feasibility and in order to ensure fuel supply and reduce transport, the assessment of the potential fuel supply for the turbines indicated they should realistically be located where fuel production occurs. Hence, the geographical context dictated the feedstock that should be used—a choice that was shown in the previous section- significantly impacts the results. Indeed, the study points out that the country-specific feedstock fed into the turbines contribute strongly to fuel production impacts, at least for climate change (section 3.2.4). Second, the impact results of the assessment of syngas from coal produced and burned in the US and China also show that the results are dependent on the geographical context. Indeed, the production of coal in both countries has different impacts due to the different mining techniques, energy sources for power demands, transport distances, etc. The results changed significantly for climate change and human health depending on whether the turbine was located in the US or China (refer to Chapter 3). Additionally, the substituted electricity is different from one country to the next because of the different long-term investments and fuel production costs, which change the short- and long-term substituted energy source. This is an interesting point, since the countries' specificities (e.g. future investment strategies, fuel production costs, technological advancements) not only impact the economic and technological perspectives of the potentially installed turbine but also affect turbine location to ensure the greatest environmental benefits from electricity generation.

4.3 Sensitivity analyses

The sensitivity analyses reveal that many inventory parameters significantly affect the results and, in some cases, may even alter the conclusions. Indeed, electricity substitution appreciably contributes to the environmental impacts. Whether the approach was the short-term (with or without incentives) or long-term affected technology, the climate change and, sometimes, resource depletion impacts were different. These results are summarised in Table 3.4. However, when the conclusions were reversed, fairly small changes in the rankings, rather than significant variations, occurred. The major changes arise from the deviation of tallow to the different market applications and are noted for every impact category. Therefore, attention should be brought as to reassess in 2020 -i.e. before the deployment of the gas turbines running on TME - the assumption of animal feed as the affected tallow application. Additionally, the sensitivity analyses of different assumptions pertaining on the indirect effects of the use of agricultural and forest residues showed significant differences, especially in the case of ecosystem quality. Thus, more information should be sought out on the sustainability of the residue removal's practice for the given regions, to conclude properly on the ecosystem damages of both scenarios. Finally, when the ReCiPe method was tested, the conclusions were similar to what had been assessed by IMPACT 20002+, except in the case of ecosystem quality, where significant impact increases were observed for ethanol from Brazil and the US and POME from Indonesia. This is of great importance, considering more and more attention has been brought to the unsustainable palm oil and sugarcane cultivations. This is mainly due to the transformation of forests to cropland. In this life cycle impacts assessment (LCIA), the impacts of land transformation were taken into account only for the climate change impact category (i.e. LUC factors). However, land transformation impacts also translate into ecosystem damages. Considering this, it is safe to say that the ecosystem damages from these cultivations have been underestimated. In Indonesia for instance, the LUC can primarily be characterised by forest cover loss on 40 million ha (Mha) of land, representing a 30% reduction in forest land (Wicke et al., 2011). Consequently, it is ill advised to use the IMPACT 2002+ method to conclude on ecosystem damages for these crops. Rather, the conclusions should be drawn from the results from the ReCiPe method.

4.4 Sources of uncertainty in the CLCA

As mentioned earlier, LCAs have important sources of uncertainty. When these uncertainties are related to the inventory flows, they may be tested using sensitivity analyses in order to verify how they may modify the study's conclusions. As seen in the results of the sensitivity analyses, several parameters significantly impact the results.

Many sources of uncertainty arise from other parameters. Indeed, because this project is a prospective study for 2020, certain assumptions were based on current market trends, which may change in the next decade or so. Also, the fuel production costs are based on projections by different institutions that vary greatly, especially in the case of alternative fuels, and are difficult to accurately assess. Furthermore, the identification of affected technologies, either for POME in Indonesia, tallow in US or electricity substitutions, involves significant uncertainty that is difficult to calculate. Finally, the type of blends that the turbine will be able to burn is not known. Indeed, the technological advances made by the partner to adapt the engine to the specificities of the different types of alternative are difficult to anticipate.

4.5 Complementarity between market potential and CLCA results

It is interesting to note that the regions and fuels that show the most potential supply in 2020 are not necessarily the ones that showed the best environmental performance. Indeed, the best environmental performances were posted by POME in Indonesia and syngas and biogas in Germany. Even so, looking at the supply potential, the forest and agricultural residues have the most potential availability. However, they both have very high production costs but not necessarily the most aggressive incentives, which are attributed to biogas in Italy and biogas and syngas in Germany. Consequently, to transform this study into an effective decision-making tool for the partner, a multi-criteria decision analysis should be carried out. Many types of MCDM methods exist, including the weighted product model or weighted sum model. MCDM makes it possible to prioritize the factors of importance for the partner (e.g. fuel production costs and incentive prices). Many researchers combine LCA and MCDM as a means of making decision-makers aware of the trade-offs between economic and environmental criteria. This is especially the case for solid waste collection methods (Janssen et al., 2010). Nevertheless, it should be noted that the objective of this study was not to identify the fuel with the most market potential but rather the ones with the best environmental performances. Indeed, the market analysis was performed solely help define the scenarios to be assessed in the CLCA.

4.6 Market assessment

Finally, the market assessment component of this study showed that the market viability of alternative fuels is dependent on many factors, which are mostly unpredictable and complex. They range from feedstock availability and forest and land protection laws to production costs, technological development, etc. Unlike many others, this study also assessed the incentives and other mechanisms for the market penetration of alternative fuels. The incentives are of great importance in terms of market potential, since they are directly linked to political decisions, technological advances, supply potential and, most importantly, production costs. Finally, it is important to note that it is not always possible to compare the market potentials of different types of fuel or feedstocks because of certain unique characteristics, especially considering that some are from renewable sources while others are fossil (e.g. syngas from coal).

4.7 Potential applicability of the results for the industrial partner

The industrial partner can now use the project results to determine where to implement its turbine for electricity generation and has received the information on the scenarios relative to the environmental impact scores and market feasibility.

There are several reasons why the partner may value the market assessments. For instance, the assessments highlights regions in which government incentives are strong and could benefit their clients (e.g. governments, electricity system operators, utilities) and, ultimately, electricity consumers. In addition, the partner could assure their clients of feedstock availability, commercial readiness and low production cost and, ultimately, anticipate their future demands.

Most importantly, the partner’s objective to evaluate potential alternative fuels on a life cycle basis has been attained, and the results could be applied to strategically position future energy markets. Additionally, from an environmental standpoint, the industrial partner could use the study as a marketing tool to further promote its technology to clients and develop a greener public image. However, it must be mentioned that, in order to divulge the LCA results to the general public, a critical review of the study must be carried out (ISO, 2006). It should also be noted that the scenarios’ environmental scores vary depending on the impact category that is assessed. Consequently, it is the industrial partner’s final responsibility to value an impact category over another according to its corporate values.

Finally, the wider CRIAQ project to explore novel fuels for gas turbines could benefit directly from the project’s results, which could help guide the researchers’ efforts to determine the types of fuels on which subsequent studies should focus. Indeed, if the researchers have a reference as to which fuel to prioritize to meet the partner’s needs, they may reconsider certain fuel types and/or redirect their efforts.

4.8 Impact of the results on the turbine market

As described in the previous chapter, the impacts of the gas turbine running on alternative fuel were lower than the turbine’s competing electricity source for a significant amount of scenarios and endpoints. The gas turbine running on the selected alternative fuel therefore has a beneficial environmental effect on the energy mix of the identified regions. This could lead to the deviation of certain dirtier (i.e. more carbon intensive) and uneconomical energy sources (i.e., wind and nuclear) to gas turbines running on these alternative fuels. Indeed, as shown in Table 1.1, the levelized cost of generating electricity from wind and nuclear are far from competitive. Consequently, gas turbines have already seen expansion to the power markets due to their low capital investments costs, and could find this study as an added proof of this technology's superiority now, however, towards a new viewpoint; environmental performance.

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CONCLUSION AND RECOMMENDATIONS

The main objective of this study was to identify where and on which alternative fuel a simple cycle gas turbine should be operating, considering environmental impacts and market feasibility. The proposed market assessment and CLCA methodology made it possible to attain this objective. This section describes the general conclusions of the project and certain methodological suggestions as well as recommendations for future work.

The study's alternative fuel market assessment considered many different factors, including potential feedstock supply, fuel production costs, state of the art, bioenergy policies, etc. The assessment determined six different regions and their relative feedstocks for the production of biogas, syngas, bioethanol or biodiesel with significant market potential in 2020. However, the literature review illustrated that many types of future potential fuel production options could be defined, and that no consensus has been reached as of yet. In light of this situation and the fact that future national and international environmental targets rely heavily on the use of biofuel in the transportation or electricity sector, the following recommendation was set out:

- A worldwide alternative fuel market assessment for these applications should be undertaken or, minimally, a standardized bioenergy market assessment methodology should be released.

However, the uncertainty of the market assessment for future fuel production is due to many factors (e.g. global commodity markets, technology developments, land protection policies) that are all highly uncertain. Therefore, any future projections will show significant error ranges that will only increase in the projected time horizons.

A prospective CLCA was carried out to determine the geographical contexts and feedstocks with most potential for future supply and technical feasibility. The results showed that German syngas and biogas posted the best overall environmental performances. Indonesian biodiesel as well, except in the case of ecosystem quality, where the ReCiPe method showed it to have very low environmental performance. Syngas from coal (Chinese and American) and Brazilian ethanol had the lowest environmental performance for all endpoint categories. Nevertheless, many issues arose from the environmental assessment, especially when considering some of the results of the sensitivity analyses. Indeed, the sensitivity analyses highlighted the uncertainty of the data used to build the inventories of the studied system. Additionally, uncertainties arose when identifying the affected technologies, due to the many opaque political and economic drivers. However, since these uncertainties are permanent and intrinsic to CLCA studies, the general recommendations and only options are to:

- Quantify the uncertainties of the collected inventory data with a Monte Carlo analysis, which, when applied in LCA studies, determines the uncertainty in the final results based on the uncertainty of the parameters entered in the model. The tested parameters may be the quality of the data itself and even the hypothesis on the affected systems. A Monte Carlo analysis may also determine whether the difference between two scenarios is significant or not.
- Use inventory processes adapted to the specific regions and assessed processes, especially in the case of biomass cultivation. Indeed, specific primary data for biomass cultivation would be beneficial, since many processes (e.g. fertilizer use, irrigation, yields, and crop rotations) are geographically dependent and may significantly contribute to the impacts.

On another note, it was shown that ecosystem quality damages due to land transformation were considerable for all energy crop based fuels. Hence, the following suggestion was made:

- Use an impact method that would take these types of impacts (i.e. land transformation on ecosystem quality) into account to significantly increase the accuracy of the study.

The challenge in identifying the ecosystem impact of land transformation lies in issues that are intrinsic to the impact characterization approach, which remains a methodological limitation in LCA. The ReCiPe method, however, managed to sidestep the issues to find endpoint factors for these damages. At length, the new IMPACT WORLD +characterization method will be released later this year and should include data on ecosystem quality loss due to land use. The method should also allow the practitioner to include land transformation impacts if there is sufficient knowledge on the type of land used and its regeneration capabilities.

The type of substituted electricity had to be determined in order to identify where there is a greater potential benefit from the use of the alternative fuels for electricity generation as compared to the competing sources of electricity generation. As previously stated, electricity substitution is an important life cycle impact contributor in each scenario. We have attempted to highlight the energy sources that are most likely to be substituted when the turbine is implemented. Energy source differences, whether looking at the long term, short term -even when assessing fuel costs through different scenarios (with or without incentives)-, may sometimes prove to be significant, especially with regards to climate change impacts. Therefore, the following recommendations should be considered:

- A dynamic energy system analysis, as discussed in section 4.1.1, is ideal to realistically assess the electricity that would actually be substituted with the injection of an extra MJ of electricity into national grid mixes. This type of assessment has proven effective in the electricity sector to guide sustainable decision making.
- Future carbon tax prices could be taken into account when assessing the marginal costs of electricity production to identify the short-term affected source of electricity. Indeed, carbon taxes have been shown to have noticeable impacts on the merit order of power systems (Newcomer et al., 2008).

Considering the previous statements and recommendations, it is possible to conclude that the identification of regions and their relative fuels for gas turbine operation was undertaken in order to consider environmental performance and market realities. This study is an example of the strategic environmental decision-making taking place within industries and governments worldwide and clearly illustrates the relevance of LCA as a support mechanism to guide and attain future environmental targets.

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APPENDIX I – Methodology to identify potential biomass and fuel supply in 2020

Following the industrial partner's guidelines, the alternative fuels that must be addressed are bioethanol, biogas, biodiesel and syngas. With this in mind, the types of feedstocks to assess for potential supply are known. For syngas, coal must be used as feedstock, but other feedstock might be assessed as well. For biodiesel, we may look at vegetable oils, animal fats, and used cooking oil. For bioethanol, energy crops such as corn, sugarcane, sugar beet and sweet sorghum, and agricultural residues (e.g. corn stover). This selection is similar for biogas as well. One of the purposes of the study was to look at 2020 markets for the partner in terms of alternative fuel demand. The first thing to do was therefore to look at the types of feedstocks and fuels that could be used at that point. Third generation biofuels (i.e. algae based fuels) were not assessed since they constitute a relatively new technology and, unlike other alternative fuels, their commercialization is not yet certain. Additionally, the market for these fuels will be limited since production costs are much higher than first and second generation fuels and will remain high until significant reductions are possible (Coyle, 2010).

The methodology for assessing the potential supply changes depend on the type of feedstock used in alternative fuel production. Indeed, the methodology follows the three different categories of feedstock that were assessed: energy crops, agricultural/forest residues and waste and coal. The following sub-sections describe the methodologies used for each category.

I.1 Energy crops

As stated in paragraph 1.1.2.2, sugarcane ethanol is currently used in a GT power plant in Brazil, proving the commercial viability of the alternative fuel in the given region. Key factors were also assessed to confirm the fact (see list below). Consequently, Brazilian ethanol was used to compare the other popular energy crop based biofuels (**Error! Reference source not found.**). In rder to assess the supply potential of the different energy crops, the crops were compared based on many factors, and only the two most viable options were selected. Only two energy crop biofuels were chosen because the study is aimed at 2020 seeing as, at that point in time, second generation biofuels are anticipated to become commercially available and competitive. The comparison factors used to determine supply feasibility are:

1. The current regional biofuel surplus
2. Future production or biomass costs
3. The energy yield per hectare (GJ/hectare)
4. Regional land availability
5. Regional bioenergy policies

The **surplus** is the sum of the production and import of the biofuel minus the exports and consumption for a given country. It is important to assess the surplus since bioethanol surpluses in Brazil have led to low market fuel price and policies to foster bioethanol use in the transport sector. This project relied on 2009 data.

An important aspect was the assessment of the economic potential of the fuel for the region, which was carried out by verifying the **biofuel costs**. Most of the time, biomass costs are less available. However, another good indicator is the biomass cost. Indeed, in the case of biodiesel, the biomass cost accounts for 65-78 % of the total fuel production costs.

The **energy yield** per hectare is important since it accounts for many different yields: the land yield, the biomass to biofuel yield and the calorific value of the fuel. It provides good insight into the ecological and technological potentials of each region and their relative fuels.

The **land availability** is the surplus land not required for food production and on which additional energy crops can be produced (Smeets et al., 2004). It was possible to know the amount of land currently used for agriculture. However, in order to quantify the land that had no current use and could potentially be used to cultivate biomass for bioenergy purposes, the surplus land category had to be verified using FAOSTAT (2010). It is important to note there may be a significant fraction of surplus land that is actually marginal land and therefore cannot be used.

Table A.I- 1: Comparison of popular crop-based biofuels

Country	Biomass	Biofuel
China	Corn	Bioethanol
Canada	Corn	Bioethanol
US	Corn	Bioethanol
	Soybean	Biodiesel
Argentina	Soybean	Biodiesel
Brazil	Sugar cane	Bioethanol
Malaysia	Palm oil	Biodiesel
Indonesia	Palm oil	Biodiesel
Africa	Jatropha oil	Biodiesel
India	Jatropha oil	Biodiesel
Europe	Rapeseed	Biodiesel

I.2 Agricultural residues and waste (manure, tallow)

In the case of biomass from waste and residues, the factors that were assessed differed to some extent. Indeed, since the production of these (mainly second generation) fuels is less commercial than the production of biofuel from energy crops, certain factors could not be assessed in the same way. In this case, there was no base scenario for comparison and so the regions and fuels were assessed. Those that posted higher supply potentials were selected. The factors that were used to determine supply potential are as follows:

1. Current fuel production or current state of the art
2. 2020 targets for and bioenergy policies
3. Available feedstock
4. Biofuel production costs

These factors are similar to the ones used for energy crops, except that they are discussed more in terms of anticipated development. Also, land availability is not taken into account, since it is the major limiting factor for bioenergy potential. However, residues and waste have no direct land use, and their availability is less limited (UNEP, 2010).

Finally, it should be noted that, when calculating the amount of available feedstock, the technical potential is limited by many different factors such as the alternative uses of products as animal feed, ecological requirements (% of sustainable removal) and the technical feasibility of collection (i.e. amount that can realistically be collected) (Smeets et al., 2004).

I.3 Coal

The method to assess the potential of future syngas from coal supply is very different from the ones used for other types of feedstock, since it is not in the bioenergy realm. Projections have therefore already been formulated for coal production, and the methodology to assess coal availability is rather simple:

1- Identify the regions with the highest coal reserves around the world and verify whether coal extraction is planned

2- Identify regions in which coal gasification plants are/will be expanded

APPENDIX II – Product system and system boundaries

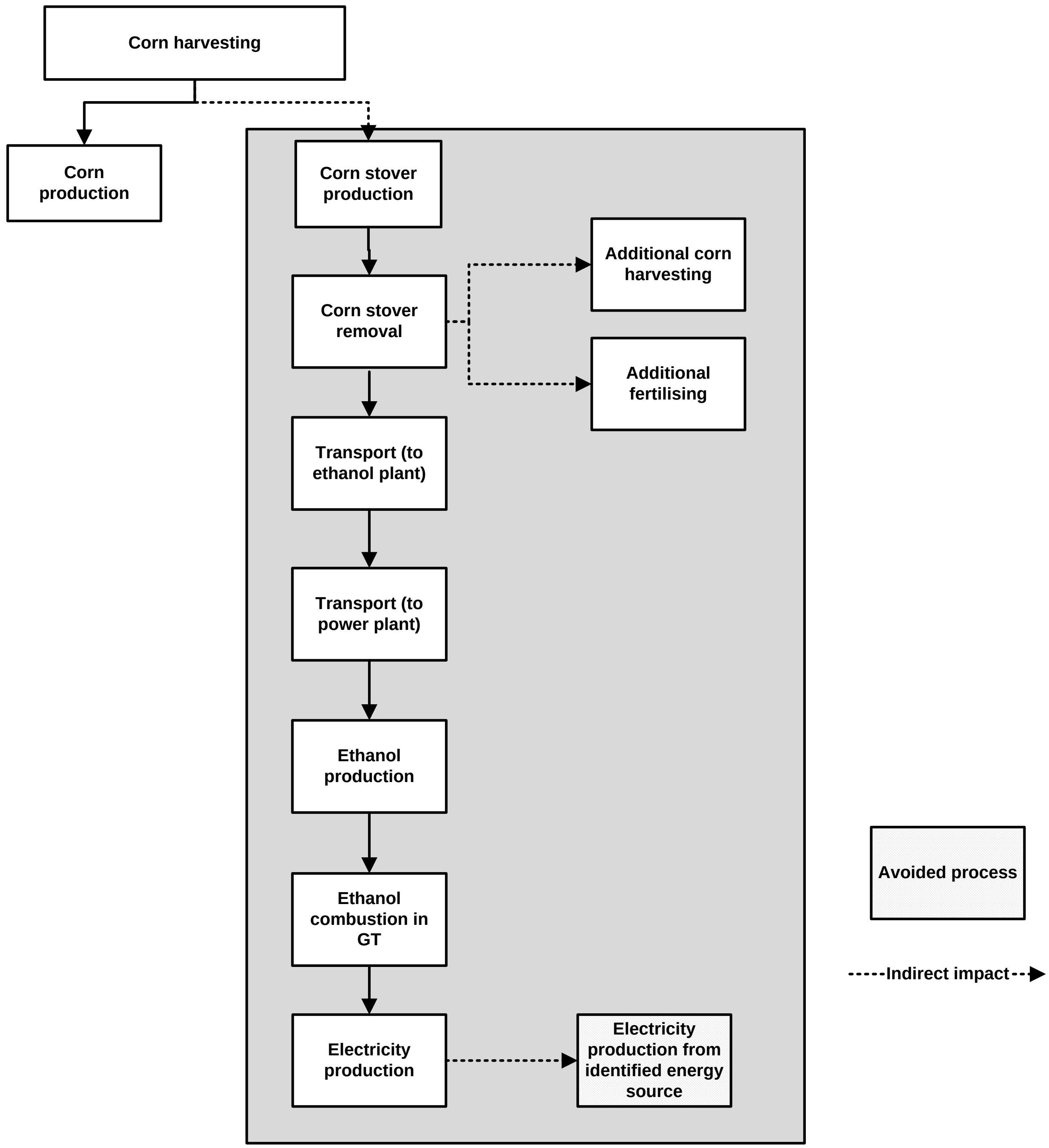

Figure A.II-1: Product system of ethanol from corn stover (US)

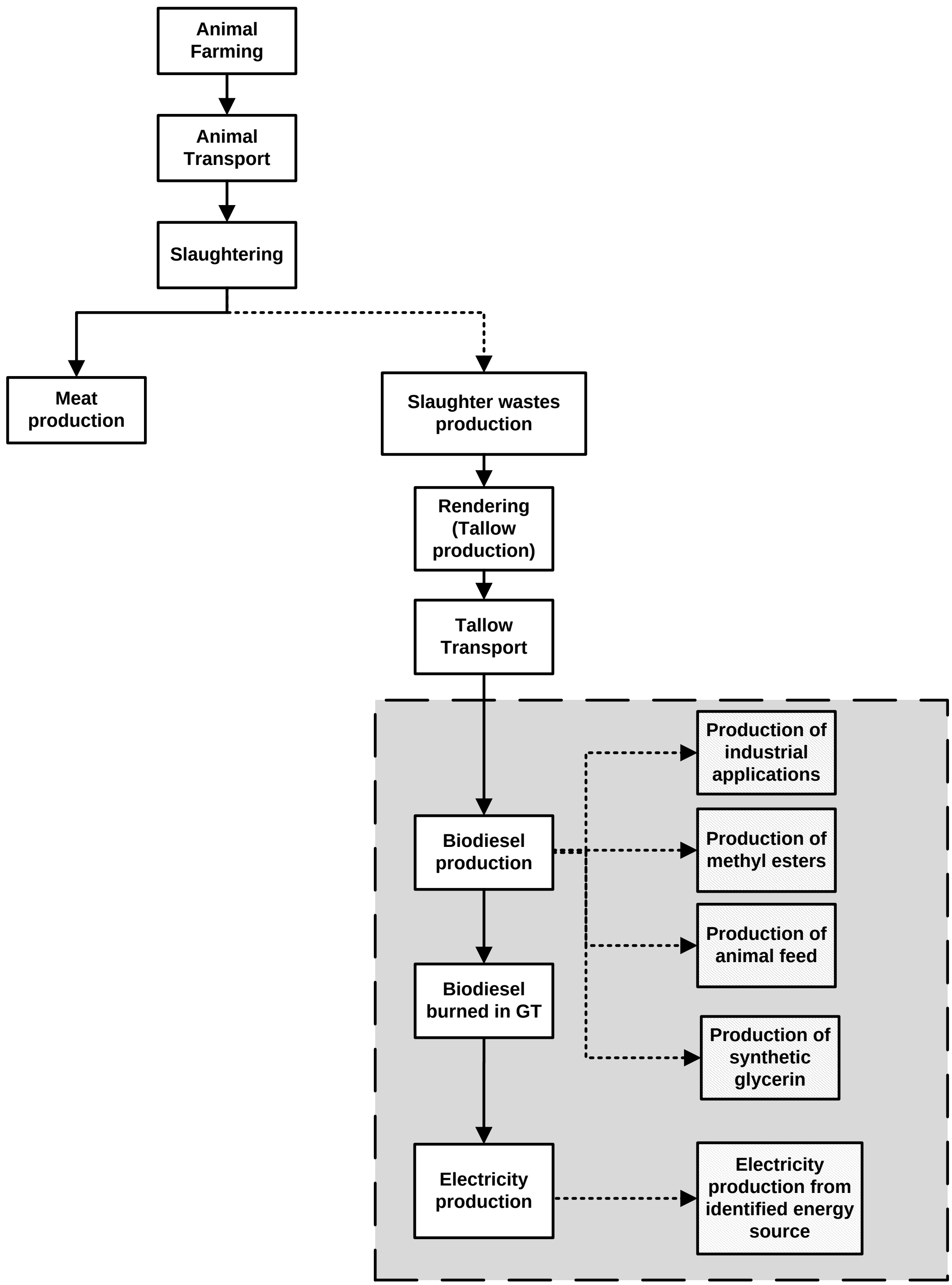

Figure A.II-2: Product system of biodiesel from tallow (US)

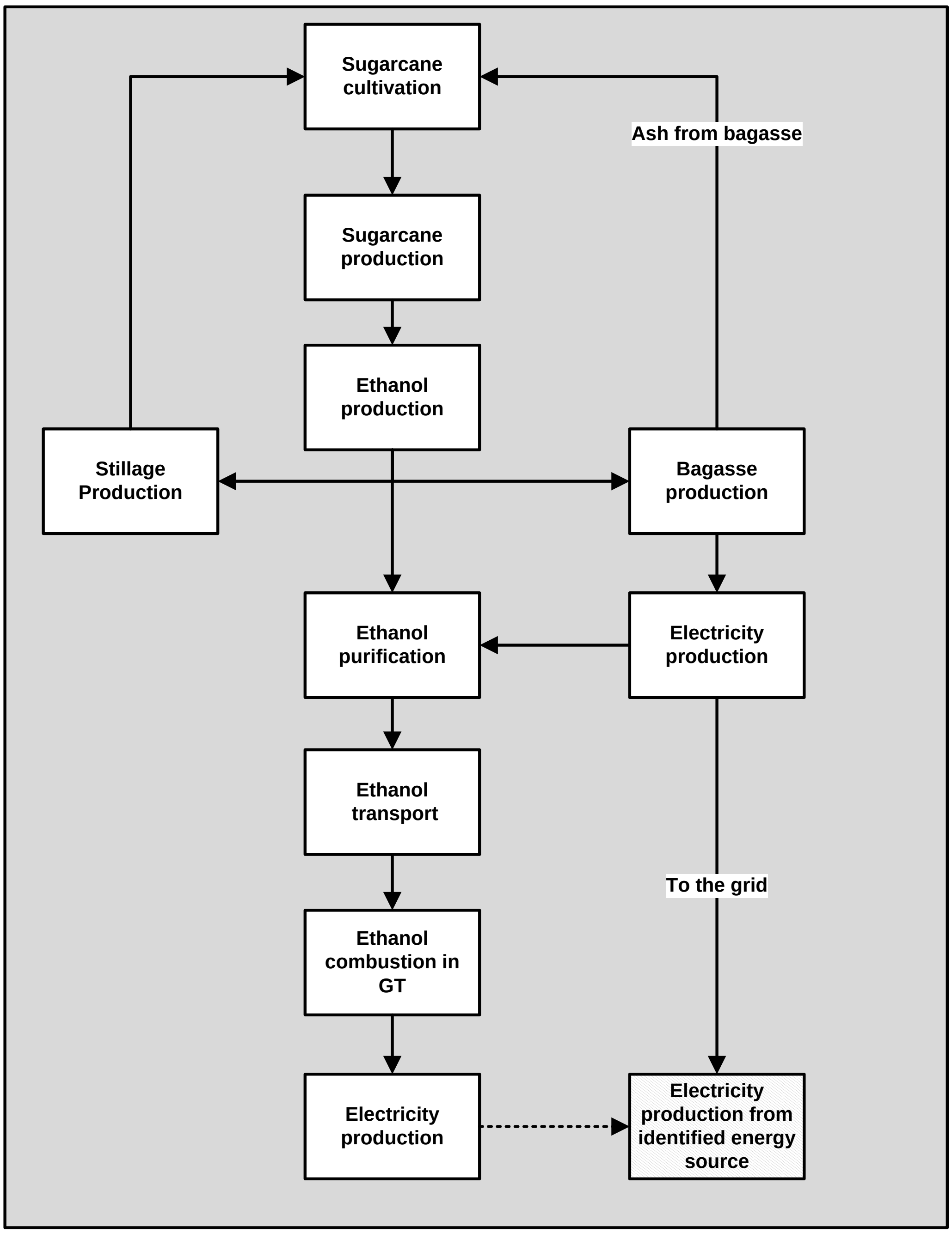

Figure A.II-3: Product system of ethanol from sugarcane (US)

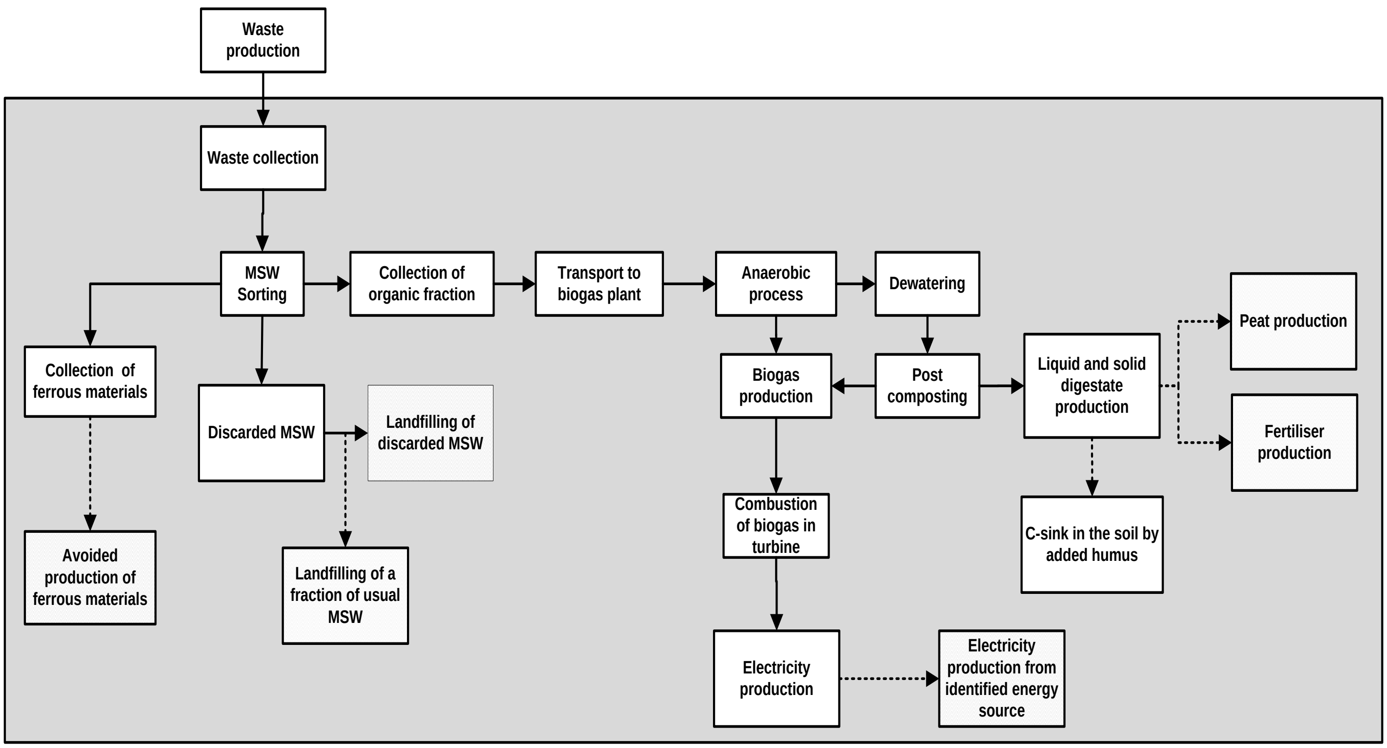

Figure A.II-4: Product system of biogas from OFMSW (Italy)

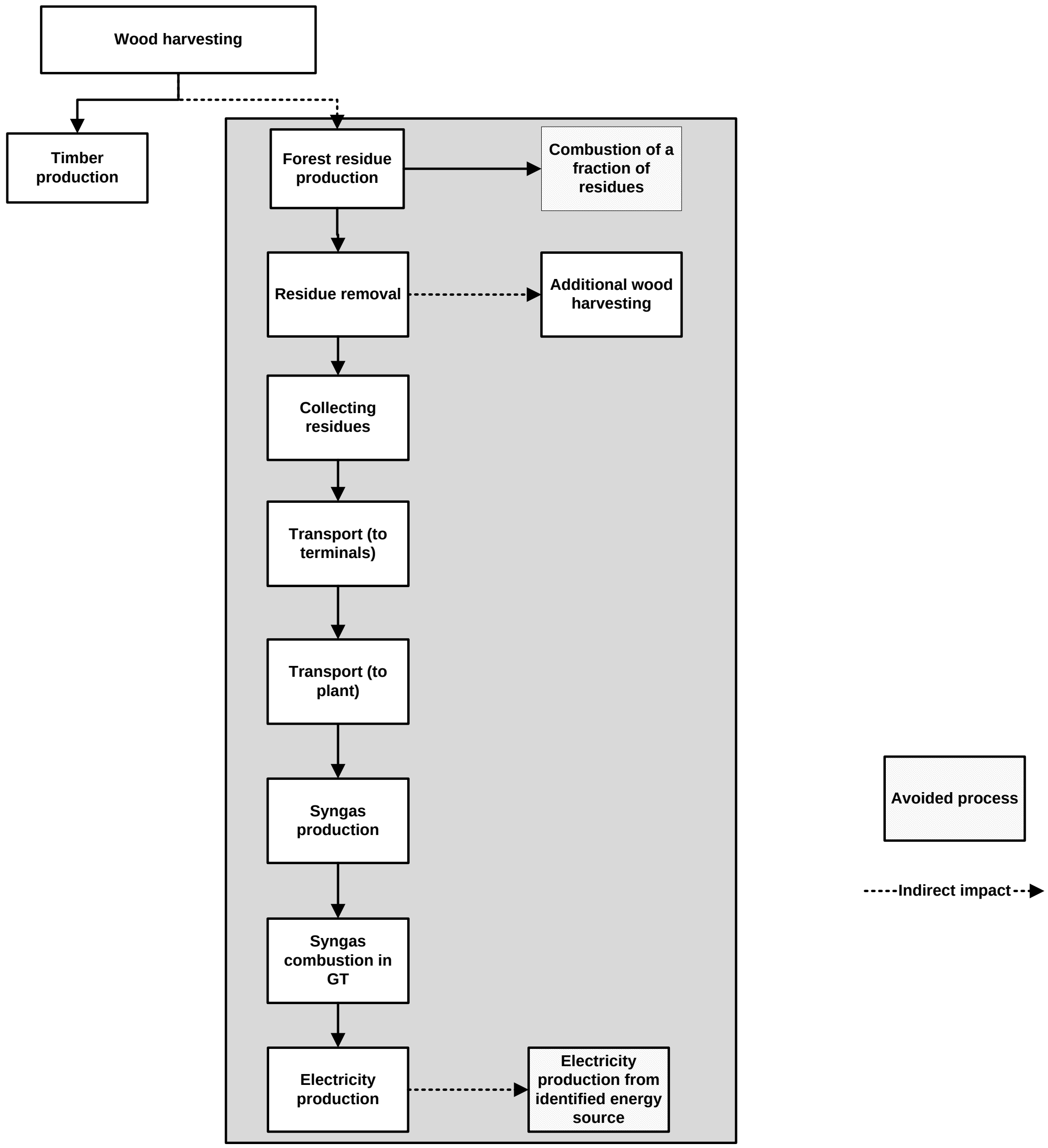

Figure A.II-5: Product system of syngas from forest residues (Germany)

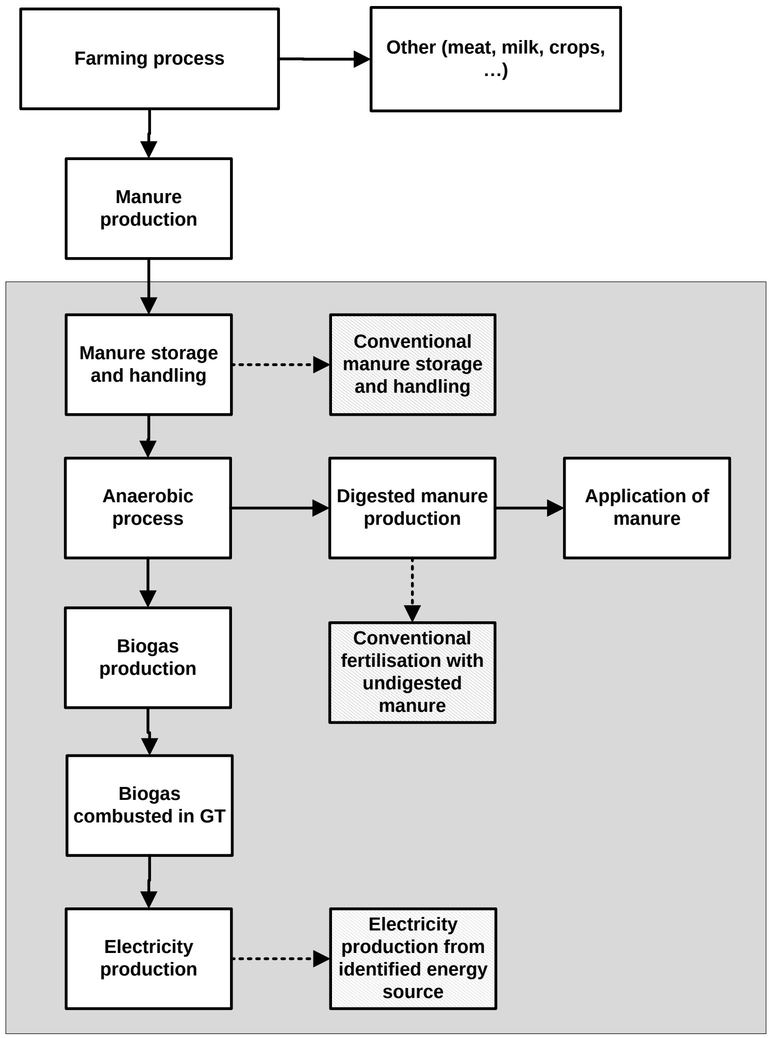

Figure A.II-6: Product system of biogas from manure (Germany)

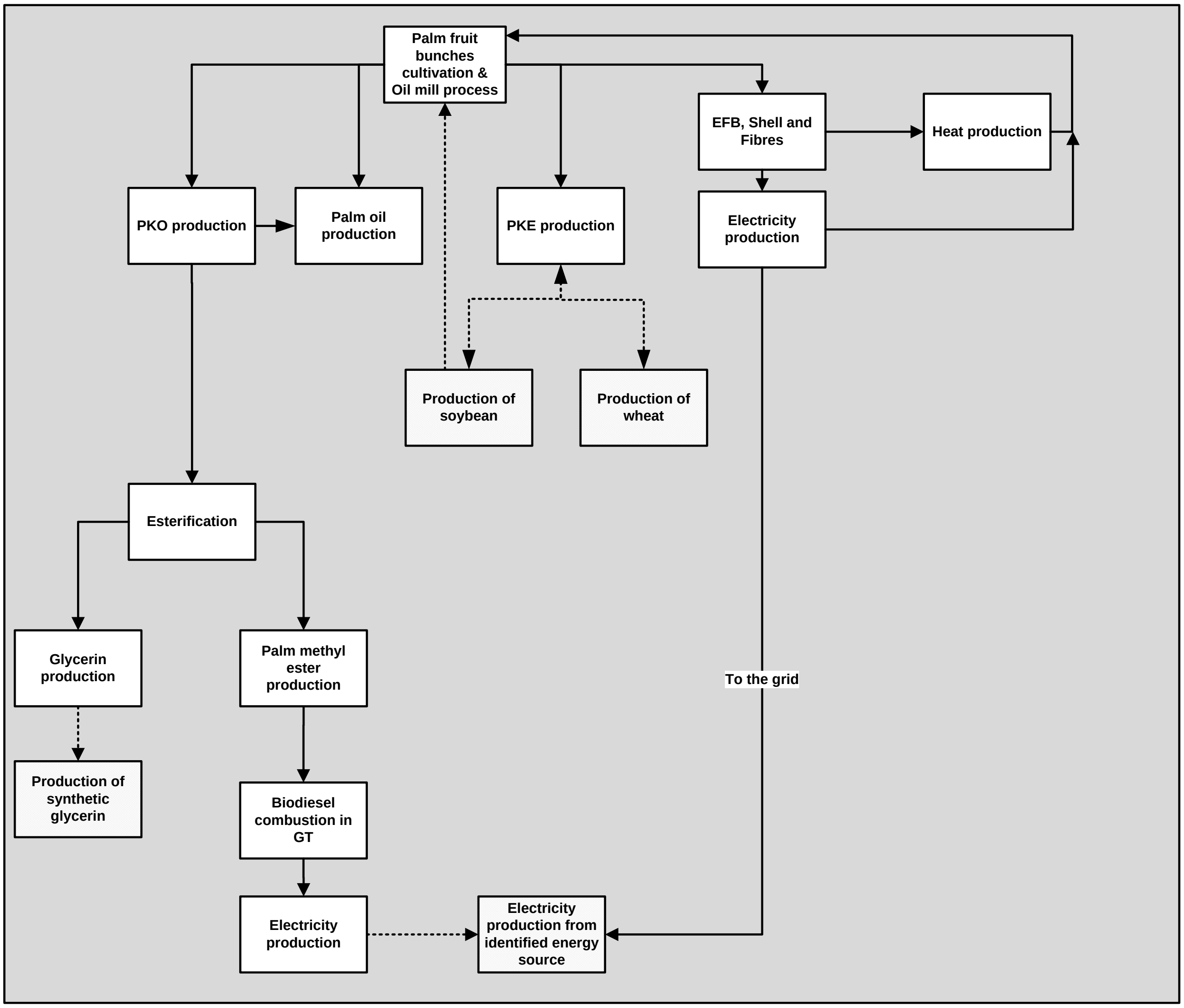

Figure A.II-7: Product system of biodiesel from palm oil (Indonesia)

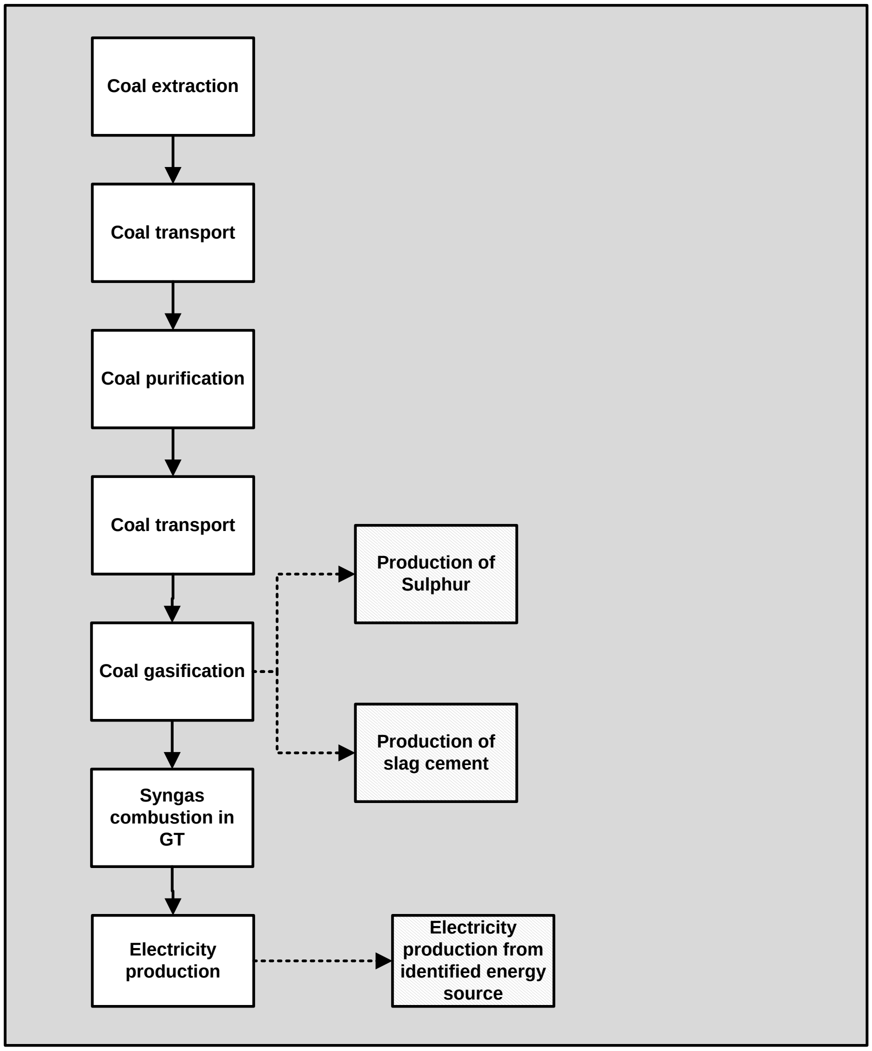

Figure A.II-8: Product system of syngas from coal (China and US)[4]

[4] In the case of syngas from coal, the product systems are the same. However, the assumptions and sensitivity analyses differ.

APPENDIX III – Indirect impacts of constrained resources calculation

III.1 Corn stover scenario calculations

The calculations are based on the fact that the inventory will change according to the percentage of corn stover removal. Indeed, the nutrient losses in terms of N, P_2O_5 and K_2O, were found and translated into added fertilizers whose production will have to be accounted for as indirect impacts. Regardless of the percentage of stover removal, it is assumed that the same amount of fertilizer will be required, since it was estimated that a linear relationship exists between the area of land that is used and nutrient loss in the soil. With a 50% removal rate, there is 50% less nutrient loss in the soil that the stover was collected from. However, twice more land is necessary to collect the same amount of stover. On the other hand, the machinery and diesel used for stover baling and transport will vary according to the removal ratio.

Additionally, it was found that with a 100% stover removal come other types of soil dysfunctions that could alter the corn yield, even if additional fertilizers were used (i.e. more corn would have to be produced to compensate for the loss in corn harvest). However, this same scenario was previously modeled by the US.EPA, which concluded that no LUC impacts were associated with the use of corn stover (US.EPA, 2009). The 2007 Renewable Fuel Standard (RFS2) study defined renewable fuels as coming from sustainable and renewable biomass. As such, they had to meet certain criteria pertaining to sustainable agricultural practices. Indeed, the corn stover used for biofuel production had to come from existing agricultural land so that no additional land expansion was necessary (ICCT, 2010).

Coincidentally, this project tested the decrease in corn yields from 100% removal scenario in the sensitivity analysis and showed that additional corn production is required to meet the same demand, leading to land expansion for corn acreage, as illustrated in Figure A.III-1.

However, in the study, no domestic direct or indirect carbon emissions related to land use changes were calculated due to a decrease in corn yields, since this scenario was actually only tested as a sensitivity analysis and, most importantly, it could be argued that the land use impacts would not be allocated to the residues but to the corn.

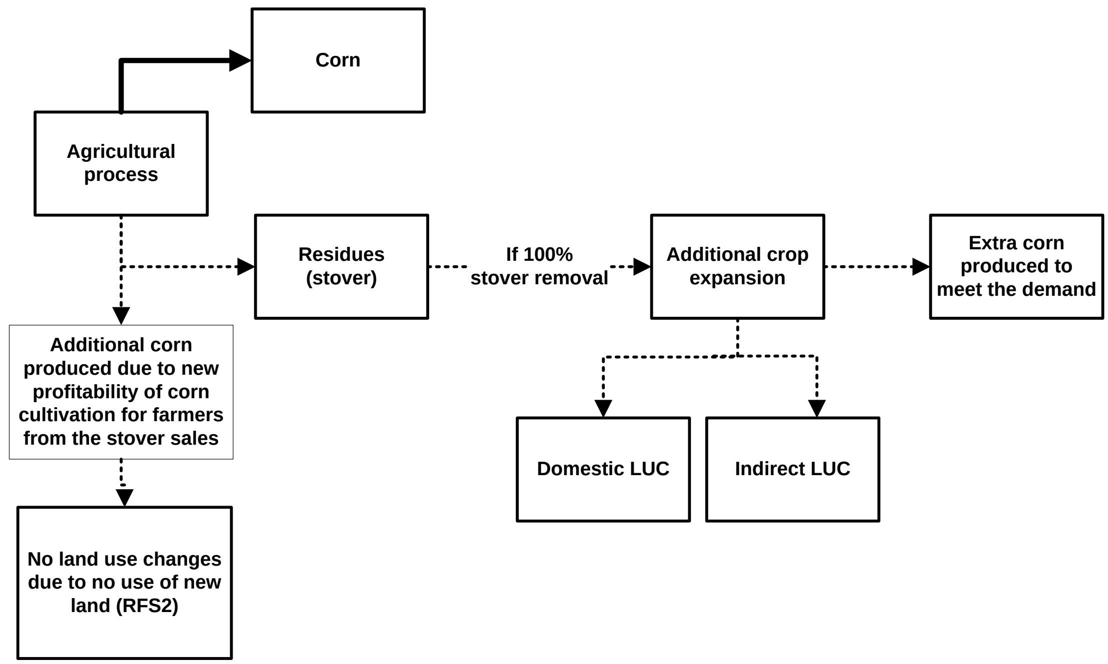

Figure A.III-1: Diagram of possible LUC impacts from corn stover use

Table A.III-1: Land needs for corn stover production based on different corn removal % (for 1 kg of ethanol)

Parameter	**Unit**	**100% removal**	**50% removal**	**25% removal**
Yield ethanol	kg dry corn stover/kg ethanol	4.49E+00	4.49E+00	4.49E+00
Yield corn stover	kg corn stover/ kg corn	1.00E+00	5.00E-01	2.50E-01
Yield corn	kg dry corn/hectare	8.17E+03	8.17E+03	8.17E+03
Corn production needed	kg dry corn/kg ethanol	4.49E+00	8.98E+00	1.80E+01
Land surface for stover baling and	hectare	5.50E-04	1.10E-03	2.20E-03

transport				

Table A.III-2: Calculation for extra fertilizer production

Type of nutrients lost	100% removal	50% removal	40% removal	Unit
N	67	34	27	lb/acre/year
P_2O_5	20	10	8	lb/acre/year
K_2O	112	56	45	lb/acre/year

1. In the case of corn cultivation in the US, the harvesting period only corresponds to 58% of the entire year. However, the land area, and not the period when the land is fertile, must be taken into account.
2. Data on nutrient loss from stover removal was taken from (Fixen, 2007)

Table A.III-3: Calculation for additional corn production (sensitivity analysis only)

	Unit	25% removal	50% removal	100% removal
Affected corn yield based on different removal percentage	Mg/ha*year	0	1.80E+00	3.30E+00
Extra corn cultivation required	ton	0	1.98E-03	7.25E-03

1. Data on affected corn yield taken from (Blanco-Canqui and Lal, 2009)
2. Affected yield for 25% removal or less or considered negligible according to (Blanco-Canqui and Lal, 2009).

III.2 Forest residues scenario calculations

The approach in this scenario aimed to assess the indirect effects of slash removal, which impacts:

1. Nutrient depletion (N and base cations): Affects long-term site productivity. The effects are noticeable four years after thinning and are still detectable ten years later.

2. Nutrient cycling: Residue removal will temporary interrupt nutrient cycling over an average of six years per thinning. In forest management, four thinnings are considered standard, resulting in 24 years of interrupted nutrient cycling over an average life span of 84 years/ tree.

3. Equipment: Soil disturbance, reducing and eliminating regrowth for several years.

The usual timber yield will therefore be affected, and additional timber production may have to be undertaken. On average, whole tree harvesting reduces tree volume growth by 5-6% in both pine and spruce stands during the first ten-year period. This was proved to come from the reduced N supply (growth reduction were still visible after ten years). The study shows no difference in the types of soil fertility that were tested, and the Finnish yields were extrapolated for German soils. Additionally, as with corn stover, no LUC changes were taken into account for very different reasons. Indeed, the tree cover removal can be a normal part of forest management. The removal of timber from a forested site does not necessarily create an environmental burden. The carbon removed from the land as timber is only a small fraction compared to the amount of carbon stocked in the soil and non-harvested trees (Müller-Wenk and Brandão, 2010). If the land is allowed to regenerate, the ecosystem effects of harvesting are carbon neutral (Martin, 2010).

Table A.III-4: Biomass residues under the typical management regime of a southern Finnish forest

Activity	Stand age (years)	Yield timber (m3/ha)	Biomass residue (m3/ha)
Pre-commercial	10-20	0	15-50
1st commercial thinning	25-40	30-80	30-50
2nd commercial thinning	40-60	50-90	20-40
3rd commercial thinning	50-70	60-100	20-40
Final harvest	70-100	220-330	70-130
Average life time	85		

1. Data from (European Biomass Industry Association, 2006)

Table A.III-5: Cultivated biomass based on timber and residue yields

Average yields (m3/ha)		**High yield (m3/ha)**		**Low yield (m3/ha)**	
Timber yield	**Biomass residue**	**Timber yield**	**Biomass residue**	**Yield timber**	**Yield residue**
0	32,5	0	50	0	15
55	40	80	50	30	30

70	30	90	40	50	20
80	30	100	40	60	20
275	100	330	130	220	70
Total cultivated biomass					
480	233	600	310	360	155

1. Data from (European Biomass Industry Association, 2006)

Table A.III-6: Hectares affected for 1 m3 of forest residues for whole tree harvesting

Total harvesting of timber (m3/hectare)			Total harvesting of residues (m3 per hectare)		
Average	Low	High	Average	Low	High
480	360	600	233	155	310

Table A.III-7: Timber production based on the same land use required to produce 1m3 of dry forest residues

m3 timber/m3 residues		
Average	Low	High
2.06E+00	2.32E+00	1.94E+00

Table A.III-8: Parameters used for the calculations

% of volume of tree growth affected	Years	Nb of years affected	Nb of harvests	Tree life expectancy			% of time tree is affected by nutrient loss		
				Average	Low	High	Average	Low	High
5.5	5.00E+01	1.00E+01	5.00E+00	8.50E+01	7.00E+01	1.00E+02	5.88E-01	7.14E-01	5.00E-01

Table A.III-9: Additional timber production from yield loss due to removal

m3 timber to be produced		
Average	Low	High
6.68E-02	9.12E-02	5.32E-02

Finally, if the slash was used, it would avoid burning on the collection sites—a practice that aims to avoid fire hazards (Government of B.C., 2011). However, since the fraction of residue burned was not known, it was tested in the sensitivity analysis.

Table A.III-10: Emissions from pile-burning of biomass in forests (for 1 kg residues)

CO_2 emissions (kg)	CH_4 emissions (kg)	PM_{10} emissions (kg)	*Fraction combusted*
1.46E+00	5.09E-03	5.54E-03	1.00E+00
6.57E-01	2.29E-03	2.49E-03	4.50E-01
4.38E-01	1.53E-03	1.66E-03	3.00E-01
2.19E-01	7.63E-04	8.30E-04	1.50E-01

1. Emissions taken from (Jones, et al., 2010)

III.3 Manure scenario calculations

1-Emissions changes from the handling and storage of raw materials and digestates

Table A.III-11: Emissions changes from the handling and storage of raw materials and digestates

Type of impact	Chemical	Quantity	Unit	Justification
Emission reduction	CH_4	1.6	kg/ton manure	Due to reduction in storage time
	NH_3	100.0	g/ton manure	Compared to open storage tanks
	N_2O	40.0	g/ton manure	Digested manure contains organic matter that decomposes less easily than conventional manure. Less energy is therefore available to the nitrous oxide-forming microorganisms, leading to an estimated average reduction of N2O emissions.
Emission increase	NH_3	250.0-310.0	g/ton manure	Spreading of digested manure (since digested manure has a higher ammonia content that can be potentially converted into NH3)

1. Data from (Berglund and Borjesson, 2006)

2- Nutrient leaching change from changed cropping practices

Nutrient leaching change occurs since the digestion of liquid manure increases its quality as a fertilizer as organic bound nitrogen is converted into ammonium available to plants. Also, there is higher precision in fertilization and lower risk of nitrogen leakage. The calculation methods consist in determining the nitrogen leaching change and how it may lead to the use of less fertilizer. Finally, since less fertilizer is used, usual fertilizing emissions are reduced as compared to the related amount. The difference was calculated.

Table A.III-12: Avoided fertilizer production due to nitrogen leaching change

Nitrogen leaching change		**Equivalent in avoided production of fertilizers**	
kg N /hectare, year	g NO3/tonne	Nitrogen (kg/tonne raw material)	Phosphorus (kg / ton of raw material)
-7.5	-1100	0.51	0

1. Data from (Berglund and Borjesson, 2006)

Table A.III-13: Factors used to calculate the reduced emissions with the use of less N fertilizers

Nitrogen (kg/tonne raw material)	Emission factor		kg emitted/kg manure
5.1 E-01	6.50E+00	Ammonia	3.32E-05
	3.10E+00	Dinitrogen monoxide	1.58E-05
	1.80E+00	Nitrogen oxides	9.18E-06
	0E+00	phosphorous (river)	0.00E+00
	0E+00	phosphorous (groundwater)	0.00E+00

	31.99E+00	Nitrate (groundwater)	7.23E-04

1. Factors taken from the ecoinvent factors for emissions

III.4 Tallow scenario calculations

1-Fatty acid applications

In the case of fatty acid applications, the substitutability of tallow and palm oil is based on their fatty acid contents (see table below). Since palm oil is used again, the system equation must be used. However, the oil demand in the final demand vector refers to the substitutability ratio for palm oil vs tallow.

$$kg\ PO * \begin{bmatrix} 1\ kg\ oil/\ kgPO \\ 18.1\ kg\ protein/kgPO \\ 0.096\ FU/kgPO \end{bmatrix} +\ kg\ SM * \begin{bmatrix} 0.233\ kg\ oil/kg\ SM \\ 430\ kg\ protein/kg\ SM \\ 1.2\ FU/kg\ SM \end{bmatrix}$$
$$+\ kg\ wheat \begin{bmatrix} 0\ kg\ oil/kg\ SM \\ 79\ kg\ protein/kg\ SM \\ 1.083\ FU/kg\ SM \end{bmatrix} = \begin{bmatrix} 0.98447 \\ 0 \\ 0 \end{bmatrix}$$

The solution to the system of linear equations is:

$$\begin{bmatrix} 1961.6\ kg\ soybean\ meal \\ 414\ kg\ wheat \\ -2278.8\ kg\ PO \end{bmatrix}$$

Table A.III-14: Fatty acid properties for tallow and crude palm oil and substitutability ratios

	Fatty acids			
	Tallow		CPO	
Type of FA	Saturated	Unsaturated	Saturated	Unsaturated

	g/100g fat product	g/100g fat product	g/100g fat product	g/100g fat product
Tallow 1	5.180 E+01	3.860 E+01	4.490E+01	4.730E+01
Tallow 2	5.040 E+01	4.00 E+01		
Average Tallow	5.110 E+01	3.930E+01		
	Ratio compared to tallow			
	1	1	1.138E+00	8.308E-01
			9.845E-01	

1. Calculations derived from (Shuangma Chemical Co., 2008)

2-Animal feed

The substitutability of tallow and wheat is defined in terms of digestible energy (Zijlstra et al., 1999). Based on this characteristic, the ratio is **1kg of tallow: 0. 0871 kg of wheat.** Consequently, the amount of additional wheat production for the scenario may be calculated from this. As for the LUC change factors, they were derived from (Bauen et al., 2010), in which the LUC factors were calculated for wheat bioethanol demand. Since ethanol production co-produces feed, other LUC that are not relevant in this case were included. Indeed, in this case, wheat expansion is the only alternative scenario to meet additional wheat demand.

3-Methyl ester

In the case of methyl ester, the substitutability comparison is based on the ability to produce the same amount of methyl ester. It was found that 0.9645 kg of PO is required to obtain the same amounts of biodiesel and tallow. Then, the same system of linear equations as for fatty acid application was used. Only e final demand vector was changed to account for the relevant substitutability ratio.

APPENDIX IV – Land use change calculations

IV.1 Calculations for ethanol from sugarcane

Table A.IV-1: ILUC factors for ethanol production (g CO2 eq/MJ biofuel)

Scenario	1	2	3	4	5	6	7	8	9	10	11	12	13
ILUC factor	18.8	19.3	16.3	16.7	15.4	13.1	22.2	11.7	16.7	7.82	24.9	27.3	26.2

1. The factors used in the study were the minimum and maximum values for the sensitivity analysis and the average for the base scenario.
2. Factors directly from (Bauen et al., 2010)

IV.2 Calculations for biodiesel from palm oil

The system of linear equations was used (see below). The protein content of wheat was found based on crude protein for poultry feed in (Lywood et al., 2009). The energy content was based on digestible energy for bovines (Zijlstra et al., 1999).

$$kg\ PO * \begin{bmatrix} 1\ kg\ oil/\ kgPO \\ 18.1\ kg\ protein/kgPO \\ 0.096\ FU/kgPO \end{bmatrix} + \ kg\ SM * \begin{bmatrix} 0.233\ kg\ oil/kg\ SM \\ 4.3\ kg\ protein/kg\ SM \\ 1.2\ FU/kg\ SM \end{bmatrix} + kg\ wheat \begin{bmatrix} 0 \\ 79 \\ 1.083 \end{bmatrix} = \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix}$$

The solution to the system of linear equations is:

$$\begin{bmatrix} 0{,}03265\ kg\ soybean\ meal \\ 0{,}05314\ kg\ wheat \\ 1{,}00761\ kg\ PO \end{bmatrix}$$

The land use changes associated with this scenario are derived from factors found in (Bauen et al., 2010).

Table A.IV-2: ILUC factors for biodiesel production (g CO2 eq/MJ biofuel)

Type of impact	Location	1	2	3	4	5	6	7	8	9	10
Expansion of palm area	Indonesia	76.11	29.65	39.74	90.5	12.45	22.54	73.3	6.78	16.87	67.63
	Malaysia	61.28	23.76	31.28	72.87	11.89	19.4	60.99	5.87	13.38	54.97
	Colombia	0.85	1.01	1.01	1.01	1.01	1.01	1.01	0.16	0.16	0.16
Avoided soybean expansion	Argentina	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.07	0.07	0.07
	Brazil	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.17	0.17	0.17
Avoided coconut expansion	Indonesia	68.33	26.62	35.68	81.26	11.18	20.23	65.81	6.09	15.15	60.73
Avoided wheat expansion	EU	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.05	0.05	0.05
	Outside EU	1.39	1.39	1.39	1.39	1.39	1.39	1.39	0.56	0.56	0.56
Additional palm production to replace soybean oil	Indonesia	0.22	0.09	0.12	0.27	0.04	0.07	0.21	0.02	0.05	0.20
	Malaysia	0.22	0.09	0.11	0.26	0.04	0.07	0.21	0.02	0.05	0.20
TOTAL ILUC Factor		68.19	25.82	34.42	81.49	12.09	20.7	67.75	5.91	14.51	61.58

1. Factors from (Bauen et al., 2010)

Table A.IV-3: Adapted ILUC factors used in the study for biodiesel production (g CO2 eq/MJ biofuel)

Type of impact	Location	1	2	3	4	5	6	7	8	9	10
Expansion of palm area	Indonesia	6.71E+01	2.61E+01	3.50E+01	7.98E+01	1.10E+01	1.99E+01	6.46E+01	5.98E+00	1.49E+01	5.96E+01
	Malaysia	5.40E+01	2.09E+01	2.76E+01	6.42E+01	1.05E+01	1.71E+01	5.38E+01	5.17E+00	1.18E+01	4.85E+01
	Colombia	7.50E-01	8.90E-01	8.90E-01	8.90E-01	8.90E-01	8.90E-01	8.90E-01	1.40E-01	1.40E-01	1.40E-01

Avoided soybean expansion	Argentina	1.90E-01	1.90E-01	1.90E-01	1.90E-01	1.90E-01	1.90E-01	1.90E-01	7.00E-02	7.00E-02	7.00E-02
	Brazil	5.00E-01	5.00E-01	5.00E-01	5.00E-01	5.00E-01	5.00E-01	5.00E-01	1.70E-01	1.70E-01	1.70E-01
Avoided coconut expansion	Indonesia	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Avoided wheat expansion	EU	8.00E-02	8.00E-02	8.00E-02	8.00E-02	8.00E-02	8.00E-02	8.00E-02	5.00E-02	5.00E-02	5.00E-02
	Outside EU	1.39E+00	1.39E+00	1.39E+00	1.39E+00	1.39E+00	1.39E+00	1.39E+00	5.60E-01	5.60E-01	5.60E-01
Additional palm production to replace soybean oil	Indonesia	2.20E-01	9.00E-02	1.20E-01	2.70E-01	4.00E-02	7.00E-02	2.10E-01	2.00E-02	5.00E-02	2.00E-01
	Malaysia	2.20E-01	9.00E-02	1.10E-01	2.60E-01	4.00E-02	7.00E-02	2.10E-01	2.00E-02	5.00E-02	2.00E-01
TOTAL ILUC Factor		1.20E+02	1.20E+02	4.60E+01	6.16E+01	1.43E+02	2.03E+01	3.58E+01	1.18E+02	1.05E+01	2.61E+01

1. The factors used in the study were the minimum and maximum values for the sensitivity analysis and the average for the base scenario.
2.
3. Adapted factors from (Bauen et al., 2010)

APPENDIX V – Systems inventory processes

V.1 Inventory processes for the CLCA of electricity generation from syngas from coal in the US

Table A.V-1: Processes for syngas from coal in the US (impact of generating 1 MJ of electricity)

Process	Amount	Unit	Comments
Avoided products			
Electricity, oil, at power plant US, modified	1	MJ	Sensitivity analysis Depending on the energy source identified varies between 0 or 1 MJ The ecoinvent dataset was modified in order to be adapted to the efficiency of the type of power plant in the given country. (IEA, 2008) and (EIA, 2010b)
Electricity, natural gas, at power plant US, modified	0	MJ	Same as previous
Inputs from technosphere			
Syngas production and distribution	2.454E+01	MJ	Amount related to the quantity of syngas required to produce 1 MJ of electricity
Auxiliary equipment	1	MJ	Amount related to the life cycle of

			the gas turbine power plant from RRC data to produce 1 MJ of electricity.
Gas turbine	1	MJ	Same as previous
Total transportation	1	MJ	Same as previous
Distribution to customer in US	1	MJ	Same as previous
Overall maintenance	1	MJ	Same as previous
Power plant infrastructure	1	MJ	Same as previous
Operation syngas coal USA	1	MJ	Emissions related to the production of 1 MJ of electricity calculated from either the literature or the Etrent software.

1- The shaded processes are identical for all systems since they are properties of the gas turbine and originate from collected RRC data. They are shown only for this system to lighten the following tables.
2- 2-Processes in italic and underlined will be detailed further.

Table A.V- 2: Syngas production and distribution process (for 1 MJ of syngas)

Process	Amount	Unit	Comments
Inputs from technosphere			
Syngas production	7.310E-02	kg	Quantity of syngas required to produce 1 MJ of electricity
Transport, natural gas, onshore pipeline, long distance	7.310E-03	tkm	Sensitivity analysis If it is an IGCC power plant, then no transport

Table A.V-3: Syngas production process (for 1 lb of syngas)

Ecoinvent process	Quantity	Unit	Comment Source
Avoided products			
Secondary sulphur, at refinery RER	1.98E-02	lb	
Blast furnace slag cement	9.11E-02 *Slag_sale	lb	Sensitivity analysis Slag sale parameter refers to the fact that there is uncertainty whether the slag will be sold on the market or disposed of.
Input from nature (resources)			
Inputs from technosphere			
Hard coal supply mix, at regional storage, US	6.30E-01	lb	
Limestone, milled, packed, at plant CH	1.61E-02	lb	
Steam, for chemical processes, at plant, RER	1.93E-01	lb	

Water completely softened	1.78E-03	lb	
Water completely softened	1.99E-01	lb	
Methanol, at regional storage	1.98E-04	lb	
Natural gas, at long distance pipeline	1.79E-05	m3	
Electricity, natural gas, at power plant US, modified	1.22E+02	kJ	
Water completely softened	1.79E-01	Lb	
Electricity, natural gas, at power plant US, modified	2.31E+02	kJ	
Synthetic gas plant/CH	3.69E-10	p	
Emissions to air			
Sulfur dioxide	1.89E-05	lb	
Nitrogen oxides	6.29E-04	lb	
Mercury	6.29E-06	lb	
Carbon dioxide, fossil	6.83E-02	lb	
Emissions to water			
Waste water	3.17E-02	m3	
Waste water	1.84E-03	m3	

Waste water	7.29E-03	m3	
Hydrogen chloride	2.73E-04	lb	
Nitrogen	4.24E-01	lb	
Emissions to soil			
Disposal			
Disposal, slag, unalloyed electr. steel, 0% water, to residual material landfill/CH U	9.11*(1-Slag_sale)	lb	<u>Sensitivity analysis</u> Slag sale parameter refers to the fact that there is uncertainty whether the slag will be sold on the market or disposed of.

All figures refer to the data collected by (Bartone and White, 2007)

V.2 Inventory processes for the CLCA of electricity generation from syngas from coal in China

The small differences between this section and the previous section on syngas from the US pertain to the type of electricity that is used since the Chinese—and not the American—grid mix is used. Also, the difference is seen in electricity substitution (see table below). Finally, the transport type and distance to the customer are different due to transcontinental shipping.

Table A.V-4: Processes for the syngas from coal in China system (impact of generating 1 MJ of electricity)

Process	Amount	Unit	Comments
Avoided products:			
Electricity, natural gas, at power plant/CHINA modified	0	MJ	Sensitivity analysis Depending on the energy source identified varies between 0 or 1 MJ The ecoinvent process was adapted to the efficiency of the power plant in the given country (IEA, 2008) and (EIA, 2010b).
Electricity, oil, at power plant China modified	0	MJ	Same as previous
Electricity, hard coal, at power plant CHINA - Modified	1	MJ	Same as previous
Inputs from technosphere			
Syngas production and distribution	2.454E+01	MJ	Amount related to the quantity of syngas required to produce 1 MJ of electricity
Auxiliary equipment	1	MJ	Amount related to the life cycle of the gas turbine power plant from RRC data for 1MJ of electricity produced.
Gas turbine	1	MJ	Same as previous
Total transportation	1	MJ	Same as previous

Distribution to customer in USA	1	MJ	Same as previous
Overall maintenance	1	MJ	Same as previous
Power plant infrastructure	1	MJ	Same as previous
Operation syngas coal USA	1	MJ	Emissions related to the production of 1 MJ of electricity.

V.3 Inventory processes for the CLCA of electricity generation from ethanol from corn stover in the US

Table A.V-5: Inventory processes for the CLCA of electricity generation from ethanol from corn stover in the US (impact of generating 1 MJ of electricity)

Process	Amount	Unit	Comments
Avoided products			
Electricity, oil, at power plant US, modified	1	MJ	Sensitivity analysis Depending on the energy source identified varies between 0 or 1 MJ The ecoinvent process was adapted to the efficiency of the power plant in the given country (IEA, 2008) and (EIA, 2010b).
Electricity, natural gas, at power plant US, modified		MJ	Same as previous
Inputs from technosphere			

Production and distribution of Bioethanol (corn stover)	2.387	MJ	Amount related to the quantity of ethanol required to produce 1 MJ of electricity (efficiency)
Operation bioethanol corn stover	1	MJ	Emissions related to the production of 1 MJ of electricity

Table A.V-6: Production and distribution of bioethanol (corn stover) (for 1MJ of ethanol)

Process	Amount	Unit	Comments
Inputs from technosphere			
Bioethanol Production (corn stover)	0.04403	kg	
Transport ethanol to refinery	0.04403	kg	
Transport fuel from refinery to regional storage	0.04403	kg	

Table A.V-7: Bioethanol production from corn stover (for 1kg of ethanol)

Process	Amount	Unit	Comments
Steam, for chemical processes, at plant/RER U	0	MJ	The steam generated by the process is not used in any way (Renewable Energy Laboratory., 2007).

Electricity, natural gas, at power plant/US modified	0.5999	kWh	Electricity is co-produced in the ethanol production process, and natural gas is considered the long-term marginal technology. Sensitivity analysis The references were not unanimous on the surplus of electricity from the production process, so 0 kWh was tested.
Inputs from technosphere			
1.Feedstock storage and handling	1	kg	For 1 kg of ethanol
2.Pretreatment & hydrolyzate condition	1	kg	For 1 kg of ethanol
3.Enzyme production	1	kg	For 1 kg of ethanol
4. Saccharification and co-fermentation	1	kg	For 1 kg of ethanol
5. Product recovery	1	kg	For 1 kg of ethanol
6. Waste water treatment	1	kg	For 1 kg of ethanol
7. Other processes	1	kg	For 1 kg of ethanol
Infrastructures	1	kg	According to a realistic ethanol production plant using 2367.744 tons dry corn stover per day.

Extra corn production needed	1	kg	For 1 kg of ethanol
Collection and transport of stover	1	kg	For 1 kg of ethanol
Extra fertilizer emissions	1	kg	For 1 kg of ethanol
Extra fertilizer production	1	kg	For 1 kg of ethanol

Table A.V-8: Pre-treatment and hydrolyzate condition (1kg of ethanol)

Process	Amount	Unit	Comments
Inputs from technosphere			
Sulphuric acid, liquid, at plant/RER	0.151	kg	
Quicklime, milled, packed, at plant/CH U	0.038	kg	
Electricity, high voltage, at grid/US U	0		Since surplus heat and electricity are produced in the process
Steam, for chemical processes, at plant/RER U	0		Since surplus heat and electricity are produced in the process
Ammonia, liquid, at regional storehouse/RER U	0.061	kg	

1. All data from (Renewable Energy Laboratory., 2007), (Wooley et al., 1999) and (Luo et al., 2009)

Table A.V 9: Enzyme production (1kg of ethanol)

ecoinvent process	Quantity	Unit	Comment
Inputs from technosphere			
Ammonia, liquid, at regional storehouse/RER U	0.017	kg	
Electricity, medium voltage, US production, at grid/US U	0		Since surplus heat and electricity are produced in the process
Emissions to air			
Carbon dioxide, biogenic	0.167	kg	
Furfural	0.004	kg	
Acetic acid	0.001	kg	
Emissions to soil			
Furfural	0.0003	kg	

1. All data from (Renewable Energy Laboratory., 2007), (Wooley et al., 1999) and (Luo et al., 2009)

Table A.V-10: Product recovery (1kg of ethanol)

ecoinvent process	Quantity	Unit	Comment Source
Inputs from technosphere			
Water, completely softened, at plant/RER U	1.72E-02	kg	

Emissions to air			
Carbon dioxide, biogenic	9.65E-01	kg	
Acetic acid	1.30E-01	kg	
Sulfuric acid	1.59E-02	kg	
Furfural	2.67E-02	kg	
Furfural	8.83E-03	kg	

1. All data from (Renewable Energy Laboratory., 2007), (Wooley et al., 1999) and (Luo et al., 2009)

Table A.V-11: Other processes (1kg of ethanol)

ecoinvent process	Quantity	Unit	Comment	Source
Inputs from technosphere				
Petrol, unleaded, at regional storage/RER U	4.78E-02	kg		
Diesel, at regional storage/RER U	2.39E-02	kg		
Water, decarbonised, at plant/RER U	1.90E+01	kg		
Electricity, natural gas, at power plant US, modified	9.98E+02	kJ		
Emissions to air				
Carbon dioxide, biogenic	5.21E+00	kg		

Acetic acid	4.90E-03	kg		
Furfural	2.75E-03	kg		
Methane, biogenic	7.00E-04	kg		
Ammonia	1.62E-03	kg		

1. All data from (Renewable Energy Laboratory., 2007), (Wooley et al., 1999) and (Luo et al., 2009)

Table A.V 12: Extra fertilizer production (1kg of ethanol)

ecoinvent process	Quantity	Unit	Comment	Source
Inputs from technosphere				
Ammonium nitrate phosphate, as N, at regional storehouse/RER U	1.95E-02	kg		
Urea, as N, at regional storehouse/RER U	8.17E-03	kg		
Ammonium nitrate, as N, at regional storehouse/RER U	1.13E-02	kg		
Diammonium phosphate, as P2O5, at regional storehouse/RER U	1.15E-02	kJ		
Potassium chloride, as K2O, at regional storehouse/RER U	6.48E-02	kJ		

Table A.V-13: Extra fertilizer emissions (1kg of ethanol)

ecoinvent process	Quantity	Unit	Comment
Emissions to air			
Ammonia	1.67E-01	kg	
Dinitrogen monoxide	4.15E-03	kg	
Nitrogen oxides	6.46E-04	kg	
Emissions to water			
Phosphorus to river	1.92E-04	kg	
Phosphorus to groundwater	1.48E-05	kg	
Nitrate to groundwater	5.51E-02	kg	

Table A.V-14: Collection and transport of corn stover (1kg of ethanol)

ecoinvent process	Quantity	Unit	Comment Source
Inputs from technosphere			
Baling/CH U	1.72E-02	p	Sensitivity analysis Machinery use changes with the % or removal of corn stover.
Transport, lorry 16-32t, EURO5/RER U	2.51E-01	tkm	Sensitivity analysis Machinery use changes with the % or removal of corn

			stover.
Storage building, chemicals, solid/CH/I U	9.00E-09	p	According to a realistic ethanol production plant using 2367.744 tons dry corn stover per day.

Table A.V-15: Extra corn production required (1kg of ethanol)

ecoinvent process	Quantity	Unit	Comment
Inputs from technosphere			
Corn, at farm/US U	1.98E+00	kg	Sensitivity analysis According to the different removal rates

V.4 Inventory processes for the CLCA of electricity generation from syngas from forest residues in Germany

Table A.V-16: Inventory processes for the CLCA of electricity generation from syngas from forest residues in Germany (impact of generating 1 MJ of electricity)

Process	Amount	Unit	Comments
Avoided products			
Electricity, natural gas, at power plant- Germany -	1	MJ	Sensitivity analysis Depending on the energy

modified			source identified varies between 0 or 1 MJ The ecoinvent process was adapted to the efficiency of the power plant in the given country (IEA, 2008) and (EIA, 2010b).
Electricity, hard coal, at power plant – Germany-modified	0	MJ	Same as previous
Electricity, oil, at power plant Germany modified	0	MJ	Same as previous
Inputs from technosphere			
Operation syngas Germany	1	MJ	Emissions related to the production of 1 MJ of electricity. They were calculated either from the literature or the Etrent software.
0. Added harvesting process	5.39E-04	m3	
1. Biomass production	2.29E-01	kg	
2. Production of Syngas (from 1 kg of dry wood)	2.29E-01	p	Data was taken from the ecoinvent process *Synthetic gas, from wood, at fluidized*

			bed gasifier/CH U but was modified to exclude feedstock production and transport, which were calculated for this specific scenario.
Avoided on-site residue burning	4.02E-1*Fraction_burning	kg	Sensitivity analysis The fraction of forest residues burned on the collecting sites was not known, and different fractions were tested.

Table A.V- 17: Additional harvesting process

ecoinvent process	Quantity	Unit	Comment
Inputs from technosphere			
Forest products, at road side	6.68 E-02	kg	Sensitivity analysis Modify amount according to different wood yield and different tree volume reduction. For the base scenario, the average wood yield was chosen and a 5% tree volume reduction. average:6,68*10^-2

			high:2,82*10^-1 low:5,32*10^-2

Table A.V-18: Biomass production (1 kg of dry wood residues)

ecoinvent process	Quantity	Unit	Comment
Inputs from technosphere			
Collection of wood residues	1	kg	
Transports of residues and chipping - C	1	kg	

Table A.V-19: Wood residues collection (for 1 kg of dry biomass residues)

ecoinvent process	Quantity	Unit	Comment	Source
Inputs from technosphere				
Diesel, at regional storage/RER U	4.78E-02	kg		
Emissions to air				
Carbon dioxide, fossil	2.49E-02	kg		
Nitrogen oxides	5.04E-01	g		

Hydrocarbons, unspecified	4.04E-02	g		
Carbon monoxide, fossil	1.35E-01	g		
Sulfur oxides	3.35E-02	g		
Particulates, unspecified	3.35E-02	g		

0. Inventory for transport of 1 kg of dry mass of residues; processes include forwarding of residues, baling of residues and forwarding, loading and unloading of trucks to roadside before first transport.
1. All data in this process from (Forsberg, 2000)

Table A.V-20: Residues and chipping transport (for 1 kg of dry biomass residues)

ecoinvent process	Quantity	Unit	Comment
Inputs from technosphere			
Transport, lorry 20-28t, fleet average/CH U	5.36E-02	tkm	
Transport, lorry 20-28t, fleet average/CH U	3.50E-02	tkm	
Transport, freight, rail/DE U	3.50E-02	tkm	
Industrial residual wood chopping, stationary electric chopper, at plant/RER U	1	kg	

Table A.V-21: Avoided on-site residue burning

ecoinvent process	Quantity	Unit	Comment
Emissions to air			
Carbon dioxide, biogenic	1.67E-01	kg	
Methane, biogenic	4.15E-03	kg	
Particulates, > 10 um	6.46E-04	kg	

V.5 Inventory processes for the CLCA of electricity generation from bioethanol from sugarcane in Brazil

Table A.V-22: Inventory processes for the CLCA of electricity generation from bioethanol from sugarcane in Brazil (impact of generating 1 MJ of electricity)

Process	Amount	Unit	Comments
Avoided products			
Electricity, natural gas, at power plant/CENTREL - Brazil	1	MJ	<u>Sensitivity analysis</u> Depending on the energy source identified varies between 0 or 1 MJ The ecoinvent process was adapted to the efficiency of the power plant in the given country (IEA, 2008)

			and (EIA, 2010b).
Electricity, oil, at power plant Brazil modified	0	MJ	Same as previous
Inputs from technosphere			
Bioethanol production and distribution_ Consequential)	2.5	MJ	Amount related to the quantity of ethanol required to produce 1 MJ of electricity (efficiency)
Operation bioethanol sugarcane	1	MJ	Emissions related to the production of 1 MJ of electricity.
Land use change	1	MJ	For 1 MJ of electricity generated

Table A.V-23: Bioethanol production and distribution (for 1 MJ of electricity**)**

ecoinvent process	Quantity	Unit	Comment
Inputs from technosphere			
Ethanol, 99.7% in H2O, from biomass, at distillation, Brazil	Efficiency_ethanol/(31 .45)	kg	Modification of the ecoinvent process to include only ethanol from sugarcane (not molasses) and no impacts from the electricity from bagassse. Since no allocation was made for the co-product of electricity from bagasse impacts were not

			allocated to it.
Transport to power plant	1	p	Transport distance was calculated from the region with highest sugarcane production to a region with dense electricity demands.

Table A.V-24: Process-Ethanol, 99.7% in H2O, from biomass, at distillation Brazil (for 0.9945 kg of ethanol)[1]

Process	Amount	Unit	Comments
Avoided products			
Electricity, natural gas, at power plant/CENTREL - Brazil	8.764E-02	kWh	The amount of substituted electricity was the surplus electricity generated for the process found in the literature.
Inputs from nature (resources)			
Carbon dioxide, in air	4.311E-01	kg	Since ethanol takes 100% of the impacts, they are not allocated to the carbon content of stillage anymore
Inputs from technosphere			
Sugarcane, at farm Brazil	1.448E+01	kg	Modified for the yield of ethanol process.

			In the sugarcane, at farm process, the land yield was also adapted to the one from projections from literature 2020: (80.2 vs 60.3ton/ha)

1. This process is for 0.9945 kg of ethanol instead of 1kg, in order to allocate 100% of the impacts to ethanol.
2. Only the modified processes are shown.

V.6 Inventory processes for the CLCA of electricity generation from biodiesel from palm oil in Indonesia.

Table A.V-25: Inventory processes for the CLCA of electricity generation from biodiesel from palm oil in Indonesia (impact of generating 1 MJ of electricity)

Process	Amount	Unit	Comments
Avoided products			
Electricity, oil, at power plant Indonesia modified	1	MJ	<u>Sensitivity analysis</u> Depending on the energy source identified varies between 0 or 1 MJ The ecoinvent process was adapted to the efficiency of the power plant in the given country (IEA, 2008) and (EIA, 2010b).
Electricity, hard coal, at power plant INDONESIA - modified	0	MJ	Same as previous

Electricity, natural gas, at power plant-Indonesia	0	MJ	Same as previous
Inputs from technosphere			
POME Indonesia (in MJ)	2.5	MJ	Amount related to the quantity of ethanol required to produce 1 MJ of electricity (efficiency)
Land use change_Palm	1	MJ	For 1 MJ of electricity generated
Operation bioethanol sugarcane	1	MJ	Emissions related to the production of 1 MJ of electricity

Table A.V-26: POME Indonesia (for 1 MJ of electricity)

Process	Amount	Unit	Comments
Avoided products			
Avoided Glycerin - PO	2.677E-02 *Efficiency_PO	kg	
Wheat grains, at farm/US U	5.314E-02 *Efficiency_PO/LHV_PO	kg	
Soybeans, at farm/BR U	3.265E-02 *1.264E+00 *Efficiency_PO/LHV_PO	kg	
Inputs from technosphere			

POME Indonesia Consequential	(1/LHV_PO)* 2.677E-02 *Efficiency_PO	MJ	Amount related to the quantity of ethanol needed for the production of 1 MJ of electricity (efficiency)
Transport, lorry >16t, fleet average/RER U	(1/LHV_PO*Efficiency_PO)*((Jambi_PP_road*0.5) + (Kalimantan_PP_Road*0.5))	MJ	For 1 MJ of electricity generated
Transport, barge tanker/RER U	(1/LHV_PO*Efficiency_PO)*((Jambi_PP_sea*0.5) +(Kalimantan_PP_Sea*0.5))	MJ	Emissions related to the production of 1 MJ of electricity.

Table A.V-27: POME Indonesia Consequential (for 1 kg of oil on the market)

ecoinvent process	Quantity	Unit	Comment
Inputs from technosphere			
Palm methyl ester, at esterification	1.1481*1.0076	kg	The ecoinvent process was modified to ensure that 100%

plant Indonesia			of the impacts were allocated to palm oil methyl ester production (1.1481). The 1.0076 comes from the quantity of palm oil required to supply 1 kg of palm oil to the market.

Table A.V-28: Palm oil at oil mill Indonesia (for 1 kg of oil on the market)

Process	Amount	Unit	Comments
Avoided products			
Electricity, hard coal, at power plant INDONESIA - modified	0.1512	MJ	From 31 MJ of surplus electricity per ton of FFB processed
Inputs from technosphere			
PFB Indonesia	4.8780	kg	Land yield from FAOSTAT for 2020.

1. Only the modified processes are shown.

V.7 Inventory processes for the CLCA of electricity generation from biogas from manure in Germany

Table A.V-29: Inventory processes for the CLCA of electricity generation from biogas from manure in Germany (impact of generating 1 MJ of electricity)

Process	Amount	Unit	Comments
Avoided products			
Electricity, natural gas, at power plant- Germany - modified	1	MJ	Sensitivity analysis Depending on the energy source identified varies between 0 or 1 MJ The ecoinvent process was adapted to the efficiency of the power plant in the given country (IEA, 2008) and (EIA, 2010b).
Electricity, hard coal, at power plant - GERMANY MODIFIED	0	MJ	Same as previous
Electricity, oil, at power plant Germany modified	0	MJ	Same as previous
Inputs from technosphere			
Biogas production from manure	2.5	MJ	Amount related to the quantity of ethanol required to produce 1 MJ of electricity (efficiency)
Operation biogas manure	1	MJ	Emissions related to the production of 1 MJ of electricity

Table A.V-30: Biogas production from manure (for 1 MJ of biogas mix)

Process	Amount	Unit	Comments
Inputs from technosphere			
Added transport	0.714*0.35	MJ	In order to have huge amounts of manure, some would have to be taken from other surrounding farms. According to the average supply of manure per farm, it would have to be 11 farms within an average distance of 17 km each (see next table).
Change in emissions	0.714*0.35	MJ	
Change nutrient leaching	0.714*0.35	MJ	
Biogas, from slurry, at agricultural co-fermentation, covered/CH U_modified	(1/26.925)*0,35	m^3	This ecoinvent process was modified to omit the impacts due to manure application.
Natural gas, high pressure, at consumer/DE U	1*0.65	MJ	Since the biogas supply is insufficient to feed the turbine during normal operation, a blend containing 65% natural gas and 35% biogas is the most likely scenario.

Table A.V-31: Calculations for manure transport

Number of heads produced in Germany 2009		(kg manure production)/ (1000 kg live animal mass*day)	Average weight of the animal	kg manure/yr	moisture content in manure	ton dry manure	GJ manure produced by an average farm
cattle	1.29E+07	7.20E+01	4.50E+02	1.60E+06	8.10E-01	3.04E+02	1.56E+05
chicken	5.93E+07	8.50E+01	2.00E+00	3.85E+04	6.40E-01	1.38E+01	7.12E+03
pigs	2.34E+07	8.40E+01	1.00E+00	7.51E+03	7.70E-01	1.73E+00	8.88E+02
total	9.57E+07					Total manure by average farm (GJ/year)	1.64E+05
						Electricity generated from 1 turbine (MJ/year)	8.54E-02
						Nb farms for operation of 1 turbine	1.17E+01

1. Data for farm specifications from (Eurostat, 2011)

Table A.V-32: Nutrient leaching change (for 1 kg of manure)

Process	Amount	Unit	Comments

Avoided products			
Ammonium nitrate, as N, at regional storehouse/RER U	0.51/1000	kg	
Emissions to air			
Ammonia	-3.32E-05	kg	
Dinitrogen monoxide	-1.58E-05	kg	
Nitrogen oxides	-9.18E-06	kg	
Nitrate	-7.23E-04	kg	

Table A.V-33: Emissions changes (for 1 kg of manure)

Process	Amount	Unit	Comments
Emissions to air			
Methane, biogenic	-1.6/1000	kg	
Ammonia	-100/1000	kg	
Ammonia	250/1000	kg	
Nitrogen dioxide	-40/1000	kg	

V.8 Inventory processes for the CLCA of electricity generation from biogas from OFMSW in Italy

Table A.V- 34: Inventory processes for the CLCA of electricity generation from biogas from MSW in Italy (impact of generating 1 MJ of electricity)

Process	Amount	Unit	Comments
Avoided products			
Electricity, natural gas, at power plant- Italy_modifed 2	1	MJ	Sensitivity analysis Depending on the energy source identified varies between 0 or 1 MJ The ecoinvent process was adapted to the efficiency of the power plant in the given country (IEA, 2008) and (EIA, 2010b).
Electricity, hard coal, at power plant ITALY - modified	0	MJ	Same as previous
Electricity, oil, at power plant Germany modified	0	MJ	Same as previous
Inputs from technosphere			
Landfilling _ Consequential)	1	MJ	For 1 MJ of electricity generated
Operation biogas OFMSW	1	MJ	For 1 MJ of electricity generated

Table A.V-35: Landfilling _ Consequential (for 1 MJ of electricity

Process	Amount	Unit	Comments
Avoided products:			
Biogas scenario 0 - Consequential	178.571	MJ	This is the credit due to the fact that usually the MSW has another waste treatment, which is landfilling. This avoids the landfilling of the waste, which avoids land occupation, emissions that are released, possible leaching, etc.
Inputs from technosphere			
Transport, municipal waste collection, lorry 21t/CH U	0	tkm	<u>Sensitivity analysis</u> If the sorting plant is at the landfill then input is 0,0179.
Transport, municipal waste collection, lorry 21t/CH U	5.70E-02	tkm	<u>Sensitivity analysis</u> If sorting is at the power plant (transport to the PP)
Transport, municipal waste collection, lorry 21t/CH U	3.90E-02	tkm	<u>Sensitivity analysis</u> If sorting is at the power plant (transport from the PP with the discarded MSW)

Sorting plant	5.69E-01	kg	The amount of MSW to sort in order to obtain the organic fraction required to produce biogas.
Anaerobic process	Efficiency_biogas/(24.04)	M3	24,04 MJ fuel/m^3 biogas
Natural gas, high pressure, at consumer/DE U	Efficiency_biogas*0.6	MJ	Since biogas production would be insufficient

Table A.V-36: Sorting plant (1 kg of restwaste for the production of 0.37 kg of OFMSW)

Process	Amount	Unit	Comments
Avoided products			
Ferrite plant/GLO U	5.0E-02	MJ	Ferrous materials collected from MSW sorting of
Inputs from technosphere			
Water, completely softened, at plant/RER U	0.00E+00	tkm	
Cast iron, at plant/RER U	3.00E-04	kg	
Polyethylene, HDPE, granulate, at plant/RER U	1.60E-04	kg	
Sorting plant for construction waste/CH/I U	1.00E-10	part	Infrastructure for 200,000 ton of treated waste/yr for

			50 years. This process is for 1 kg of restwaste.
Diesel, at regional storage/RER U	2.94E-04	kg	LHV=34 MJ/kg for diesel
Electricity, medium voltage, at grid/IT U	5.10E-02	MJ	
Transport, lorry >32t, EURO3/RER U	1.20E-03	kgkm	
Outputs to technosphere (waste and emissions to treatment)			
Disposal, municipal solid waste, 22.9% water, to sanitary landfill/CH U	5.00E-02	kg	

1. (Arena et al., 2003)

Table A.V-37: Biogas scenario 0 – Consequentiel (for the landfilling of 1 g of MSW)

ecoinvent process	Quantity	Unit	Comment	Source
Input from nature (resources)				
Clay, unspecified, in ground	4.47E-02	g		
Inputs from technosphere				
Reinforcing steel, at plant/RER U	4.20E-07	kg		
Polyvinylchloride, at regional storage/RER U	1.45E-08	kg		

Pig iron, at plant/GLO U	4.89E-07	kg		
Electricity, medium voltage, at grid/IT U	9.63E-07	kWh		
Diesel, at regional storage/RER U	6.24E-04	g		
Polyethylene, HDPE, granulate, at plant/RER U	1.25E-04	g		
Polyethylene, HDPE, granulate, at plant/RER U	6.06E-04	g		
Emissions to air				
Carbon dioxide, biogenic	1.78E-01	g		
Carbon monoxide, biogenic	1.19E-01	g		
Nitrogen oxides	1.07E-01	g		
Methane, biogenic	2.10E-02	g		
Disposal				
Disposal, municipal solid waste, 22.9% water, to sanitary landfill/CH U	1.00E+00	g		

1. *(Aren et al., 2003)*

Table A.V-38:Anaerobic process (for 1 m3 of biogas generated)

ecoinvent process	Quantity	Unit	Comment	Source
Avoided products				
Compost, at plant/CH U	0.00E+00	kg		
Ammonium nitrate, as N, at regional storehouse/RER U	4.00E-03	kg		
Diammonium phosphate, as P2O5, at regional storehouse/RER U	1.50E-03	kg		
Potassium nitrate, as K2O, at regional storehouse/RER U	3.00E-03	kg		
Peat, at mine/NORDEL U	1.40E-01	kg		
Inputs from technosphere				
Biogas, from biowaste, at storage_ modified	1.00E-01	kg		
Digested matter, application in agriculture_ Modified	0	kg		
Emissions to air				
Carbon dioxide, fossil	8.00E-02	kg		
Disposal				
Disposal, biowaste, to anaerobic digestion_Modified	1	kg		

1. Data from (Schleiss, 2008)

V.9 Inventory processes for the CLCA of electricity generation from biodiesel from tallow in the US

Table A.V- 39: Biodiesel production and distribution (for 1 MJ of electricity)

ecoinvent process	Quantity	Unit	Comment	Source
Inputs from technosphere				
Vegetable oil methyl ester, at esterification plant	0.026*Efficiency_BD_UCO*1.148	kg		
Transport, lorry >16t, fleet average/RER U	Transport_Fuel_to_PP* 0.026*Efficiency_BD_UCO	kg		

Table A.V-40: Vegetable oil methyl ester at esterification plant (for 1 kg of biodiesel)

ecoinvent process	Quantity	Unit	Comment
Avoided products			
Avoided glycerin	1	kg	
Inputs from technosphere			
LUC_Fatty_acid	0.109*1.101	kg	<u>Sensitivity analysis</u> Depending on the market application that

			is affected
LUC_Methyl_ester	1.101*0	kg	Same as previous
Methyl ester scenario	1.101*0	kg	Same as previous
Fatty acid scenario	1.101*0	kg	Same as previous
Animal feed scenario	1.101*1	kg	Same as previous
Tallow, at plant USA	1.101	kg	

1. Other processes are not modified from the original ecoinvent process.

Table A.V-41: Methyl ester scenario

ecoinvent process	Quantity	Unit	Comment	Source
Avoided products				
Wheat grains, at farm/US U	0.053*0.937	kg		
Soybeans, at farm/BR U	0.033*1.264*0.937			
Inputs from technosphere				
POME Indonesia (en kg) blank scenario for US	0.937	kg		

Table A.V-42: Fatty acid scenario

ecoinvent process	Quantity	Unit	Comment	Source

Avoided products				
Wheat grains, at farm/US U	0.961*0.0323*1.264	kg		
Soybeans, at farm/BR U	0.961*0.053			
Inputs from technosphere				
POME Indonesia (en kg) blank scenario for US	0.961	kg		

Table A.V-43: Animal feed scenario

ecoinvent process	Quantity	Unit	Comment	Source
Inputs from technosphere				
Wheat grains, at farm/US U	0.937	kg		

APPENDIX VI – Results of the assessment of potential alternative fuel supply in 2020

VI.1 Alternative fuel policies and support mechanisms

Successful bioenergy penetration depends on the competitiveness of bioenergy with other energy sources and the competition between alternative biomass uses. Policies and regulations play a crucial role in promoting biomass energy use (bioelectricity in particular) and ensuring the sustainability of biomass fuel chains. In order to seek out the regions with most bioenergy potential, national policies and regional targets were therefore assessed. This section demonstrates that the selected countries have significant bioenergy objectives and support mechanisms for major market penetration.

VI.1 .1 Germany

Targets

The German Gas Association set a target for the gas industry to reach 10% use of biogas in the transportation sector and 20% by 2020 (Jonsson, 2006). This illustrates the advancements of the biogas technology in Germany and feedstock availability. At the same time, the European Commission presented a directive to promote a significant amount of renewable energies in overall EU energy consumption by 2020 that contains a series of elements to create the necessary legislative framework. The directive will ensure that the EU reaches a 20% share of energy from renewable sources by 2020, while target percentages vary for each EU member state. In fact, the directive sets the legislative framework that should ensure an increase of 18% of RES for Germany by 2020 (EREC, 2009).

Support mechanisms

Many support mechanisms exist to promote bioenergy, bioelectricity, biofuel or specifically biogas production in Germany. Excerpts from these support schemes are presented below.

- Feed-in tariffs (FITs): Germany, Spain, and Denmark have enacted FITs that guarantee above-market rates for electricity generated from renewable sources. For example, the price premium for electricity produced from renewable sources including wind, biomass, and biomethane is 40% in Germany (EIA, 2010b).
- EEG (Renewables Energy Act) - Basic biomass compensation: The overall goals of this mechanism is to push the share of renewable power production up to 30% by 2020, develop a CO_2 reduction program and introduce new technologies for the growth of renewable generation capacity. The remunerations are in terms of €cents/kWh and depend on the capacity of the facilities (GlobalData, 2011).
- EEG biomass bonuses: They represent remunerations offered to the biomass electricity generating facilities in the new Renewable Energies Act. Many are specifically dedicated to biogas use and biomass gasification, especially in the case of woody biomass, since it is the most important source of bioenergy in Germany and a fourth of the wood production is used to generate electricity (GlobalData, 2011).
- EU Biomass action plan: It was designed to speed up the expansion of bioenergy in Europe and pursues the objectives to double biomass energy production in Europe and lay the foundations for a further increase in biomass energy production by 2020 (GlobalData, 2011).
- Directive on bioenergy demonstration projects: The Federal Ministry of Food, Agriculture and Consumer Protection issued a directive making the FNR able to support bioenergy demonstration projects. The support is either provided by investment grants or an allowance on operating costs (GlobalData, 2011).

Additionally, the German parliament decided to maintain no taxation on biogas until 2020 as long as the biogas ratios are reached (Jonsson, 2006). As long as European governments support these price premiums for renewable electricity, robust growth in renewable generation is likely to continue.

VI.1 .2 Italy

Targets

The Italian Renewable Energy Action Plan derived from the EU's directive on renewable energy has set a bioenergy target of 17% by 2020 (Jonsson, 2006). Indeed, 9.815 ktoe of bioenergy should be used as an energy source for electricity generation, heating and cooling and transportation fuel. In this action plan, a specific target exists for electricity production directly from biogas sources. In that respect, the plan establishes a 6.02TWh minimum for electricity generation (Italian Ministry for Economic Development, 2009).

Support mechanisms

There are many mechanisms in Italy to promote the production and use of biomass for energy purposes, especially in the case of its use in electricity generators. The following are the main mechanisms that are currently implemented in Italy:

- Quota obligation system/renewable portfolio standard: An obligation for electricity generators to feed a given proportion of electricity generated from renewable energy sources into the power system.
- Interconnection standards: Provide technical support, procedures and more to ensure that renewables can be efficiently and safely connected to the grid with a priority connection from other fuel sources.
- Feed-in tariff system: Tariffs differ according to the type of renewable energy source. Specific tariffs for biogas from landfills are currently in place.
- Green certificates – 2% renewable market: Referring to the earlier quota obligation, the law requires that producers provide 2% of their annual production from renewable sources. If the suppliers have no clean energy, they can use energy from other companies by buying green certificates.

- Incentives for renewable energy production: As announced by the Ministry of Environment and Land and Sea Protection, Italy plans to offer incentives for investments in renewable energy production, and biomass plants are one of the candidates.

The EU's targets are subject to production being sustainable, second-generation biofuels becoming commercially available and the fuel- quality directive being amended to allow for adequate blending levels (Council of the European Union, 2007).

VI.1 .3 United States

Targets

In the future, corn may cease to be the main feedstock for US ethanol production if lignocellulosic biomass (agricultural and forestry residues, dedicated energy crops) is successfully developed and commercialized as an alternative. The 2007 Energy Independence and Security Act established more ambitious quantitative targets, stipulating a volume of 9 billion gallons of renewable fuels by 2008 and a phased increase to 36 billion gallons by 2022—21 billion of which should be covered by advanced biofuels (of which 16 billion from cellulosic biofuels and 5 billion from undifferentiated advanced biofuels).

Support mechanisms

The 2005 Act also continued funding the Biomas Program, providing more than US$500 million to promote use of biotechnology and other advanced processes to make biofuels from cellulosic feedstocks cost-competitive with petrol and diesel, to increase the production of bioproducts that reduce the use of fossil fuels in manufacturing facilities and to demonstrate the commercial application of integrated bio-refineries that use cellulosic feedstocks to produce liquid transport fuels, high-value chemicals, electricity and heat.

In terms of grants, the 2007 Energy Independence and Security Act authorized US$500 million annually for the fiscal years 2008–15 for the production of advanced biofuels with at least an 80 percent reduction in life-cycle greenhouse gas emissions relative to current fuels. It likewise foresaw a US$200 million grant programme for the installation of refuelling infrastructure for ethanol-85.

Presently, several industries are buying power from dedicated biomass facilities established with the help of financial incentives from the federal and state governments. More important than tariffs and subsidies are the use of targets from the RFS (Renewable Fuels Standard), since a strong RFS would mean that subsidies were not required to ensure the economic viability of biofuels. Indeed a RFS would dictate that a gasoline supplier would have to procure a certain percentage of their production from renewable national resources.

Federal incentives (GlobalData, 2011)

1. Production tax credits for dedicated energy crops and farm and forest waste (USD/kWh)
2. Investment tax credits on facility costs
3. Renewable energy production
4. Renewable energy grant

State incentives (GlobalData, 2011)

1. Clean renewable energy bonds: Allows the investors to loan without interest, and the bank receives the interest money from the government
2. MACRS: Depreciation deduction
3. RPS: Requirements for electricity supply companies to produce a specific amount of their electricity from renewable energy sources
4. Net metering: To allow renewable projects connected to the transmission line to send excess energy to the electrical grid for a credit towards the energy costs.

VI.1 .4 Brazil

Targets

The goal of the Brazilian Agroenergy Plan 2006–2011 is to ensure the competitiveness of Brazilian agribusiness and support specific public policies, such as social inclusion, regional development and environmental sustainability. Based on the USDA's long-term projections, sugarcane is expected to increase from 8 million hectares in 2008 to 10 million hectares by 2020 to meet the anticipated ethanol targets (USDA, 2011).

Support mechanisms

The support mechanisms are divided into two types: support for ethanol feedstock and support for ethanol production. The most significant agricultural sector-specific policies have been aimed at making credits available for production and investments. These policies have been buoyed by marketing support programs. By 2020, the credit available for sugarcane should reach an all-time high of $3.1B (USDA, 2011). The Brazilian government implemented policies designed to support ethanol production that include price supports, tax exemptions, guaranteed markets along the supply chain and mandated blending rates. The tax incentives for ethanol fuel production involve favourable tax treatment at the pump, which changes on a monthly basis based on gasoline prices to remain competitive.

The industry has made significant investments, expanding production and modernizing technologies. An important factor in domestic market development in recent years has been the investment of the automobile industry in bi-fuel or dual-fuel alcohol–petrol cars, also referred to as flex-fuel vehicles, which are able to run on a blend of petrol and ethanol.

VI.1.5 Indonesia

Targets

The government of Indonesia has set goals to reach 2% biofuels in the energy mix by 2010 (5.29 million kiloliters) and up to 3% by 2015 (9.84 million kiloliters) and 5% by 2025 (22.26 million kiloliters) (APEC, 2011).

Support mechanisms

A major challenge to achieving these goals is financing, and the government has provided a set of incentives to attract domestic and foreign investors. In order to adjust to the changes in the fuel market in Indonesia, the biofuel production subsidies vary according to petroleum prices. In the energy diversification programs, biodiesel is seen as having great potential for many energy uses, including transportation fuels, industrial, power plants and household uses. Indonesia plans to invest into biopower, since the country's current and future biomass production potential is significant (APEC, 2011).

VI.2 Summary of results of alternative fuel feedstock supply and technological development

Table A.VI-1: Results of feedstock supply and technological developments for energy crop based biofuel

	Net trade of biofuel	Current fuel production	Energy yields (GJ/hectar)	Biofuel production costs	Agricultural land available for dedicated energy crop
Sugarcane ethanol in Brasil	1,169.00 million gallons (2009)	7749.00 million gallon of ethanol (2009)	159.00	0.227 USD/liter	152,404,000.00 hectares (Nassar, 2008)
Palm oil in Indonesia	117.00 million gallons (2009)	105.00 million gallons of biodiesel (2009)	126.00	0.477 USD/liter	26,015,372.00 hectares (Tambunan and Jetro, 2006)

Table A.VI-2: Results of feedstock supply and technological developments for non-energy crop based biofuel

	Current fuel production or current state of technology	Available quantity of biomass	Biofuel production costs	Relative number of turbines that could be operated with the feedstock amount*
Ethanol from corn stover in USA	10.10 million gallons of cellulosic ethanol (2010) Early commercialization of lignocellulosic ethanol. There are six commercial lignocellulosic ethanol plants under construction.	74.80 millions of sustainable removed corn residues (2005)	0.61 USD/liter	5 (only with corn stover) 115 (for overall agricultural) residues
Biogas from manure in Germany	1696.00 ktoe biogas from overall agricultural wastes 4,000.00 biogas plants (mostly farm scale digestors but more and more centralized anaerobic digestors)	3.84*10^7 tons dry manure (cattle, poultry, swine)	0.78 USD/liter	1.00 (from current biogas production) 117.00 (from manure availability)

	Country in Europe with the strongest growth in the biogas production sector. Commercial stage			
Biodiesel from tallow in USA	88 million gallons per year (2010) Commercial stage, many high capacity facilities (e.g. 60 million gallons per year)	12 billion pounds of animal fat; 23 billion pounds of vegetable oil (Averages 1995-2005)	0.56USD/liter	115 (animal fat)
Biogas from OFMSW in Italy	406 ktoe with about 80% coming from MSW landfills. Commercial stage	31,1 million metric tons of MSW generated in 2004 11,000,000 tons MSW per year (2009) 6,530,982 tons of MSW from landfill sites that have high enough amounts of MSW for turbine operation	0.2352 USD/liter	<1* 15 (between 35-75% biogas in mix)

Syngas from wood in Germany	Twelve commercial gasification plants in the country. (early commercial)	170 PJ/year of forest residues 330 PJ/year of forest residues and forest industry by-products [6]	0.067 USD/liter (van Ree et al., 2005)	105 204

*Operation based on a simple cycle gas turbine for an average operation time

Table A.VI-3: Results of feedstock supply and technological developments for coal based fuel

	Current fuel production	Available quantity of feedstock	Fuel production costs	Relative number of turbines that could be operated with the feedstock amount*
China	Production of 2,614,593 tons of coal (2008)	Coal reserves: 126,215.00 million tons [7]	11 USD/GJ	NA

USA	Production of 1,060,228 ktons of coal (2008)	Coal reserves: 260,551 million tons [7]	15 USD/GJ	NA

VI.3 Additional results for feedstock and fuel potential in 2020

1-Energy crops

Sugarcane ethanol from Brazil

Brazil is not in the world's largest coal or oil consumer but was included in our study for two main reasons. First, it is the only country in the world to commercially use an alternative fuel in a gas turbine system similar to the one studied. Second, Brazil shows great potential viability for ethanol production.

GE and Petrobas have implemented the only plant in the world that uses ethanol in their gas turbine at a commercial level. The plant located in Juiz de Fora, Brazil, runs on a simple cycle and has two gas turbines, one having a modified combustion chamber capable of burning both ethanol and natural gas. It may be said that Brazil is a region in which it is profitable to invest in a gas turbine running on alternative fuels, making Brazilian sugar cane ethanol a reference scenario to compare the alternative fuels and feedstock of other regions.

In order to determine whether sugar cane ethanol in Brazil really was a viable alternative, the key factors were analyzed: the net trade of ethanol in the country, production costs, the yield per hectare of land and land availability. Ethanol production totalled 7.749 million gallons in 2009, making it by far the highest production of bioethanol or biodiesel in the world. The net trade is very important to consider here, since even if biofuel production is high, the consumption rate in the country could yield a negative fuel supply. In the case of Brazil, even with a high consumption rate, the net trade is still 1.169 million gallons, while the second highest net trade was American biodiesel from soybean at 322 million gallons (Food and Agricultural Policy Research Institute (FAPRI), 2009). Looking at the market cost of biomass, Brazilian sugarcane again posted the lowest biomass cost in 2007 at US$19/ton compared to European colza and wheat, American corn, Chinese corn and Argentinean soybean (FAO, 2010). As for biomass yields, Brazilian sugar cane has the highest with 159 GJ/ hectare, rivalling with Malaysian and

Indonesian palm oil with respectively 142 and 126 GJ/hectare (Ballerini, 2006). Finally, Brazil showed that there was still a considerable amount of land that could be transformed to accommodate energy crop cultivation (FAO, 2010).

Palm oil biodiesel from Indonesia

In order to find the best crop-based biofuels and regions, the most popular contenders were compared to Brazilian ethanol (Table A.VI-4) based on the same key factors as the ones mentioned previously. Indonesia has proven to have good potential. In fact, Indonesia's biodiesel ranked fifth for highest net trade with 117 million gallons in 2009 (FAPRI, 2009). Indonesia follows Brazil for the lowest biomass cost with $US67/ ton (FAO, 2010).As previously stated, Indonesia's had biomass yields rivalled with those posted by Brazil. However, land availability was shown to be scarce as compared to Europe, India and China, where land availability was higher than cultivated land area (FAO, 2010).

Table A.VI-4: Comparison of crop-based biofuels

Country	Biomass	Biofuel
China	Corn	Ethanol
Canada	Corn	Ethanol
US	Corn	Ethanol
	Soybean	Biodiesel
Argentina	Soybean	Biodiesel
Brazil	Sugar cane	Ethanol
Malaysia	Palm oil	Biodiesel
Indonesia	Palm oil	Biodiesel

Africa	Jatropha oil	Biodiesel
India	Jatropha oil	Biodiesel
Europe	Rapeseed	Biodiesel
	Wheat	Ethanol

2-Agricultural residues and waste (manure, tallow, OFMSW)

Ethanol from corn stover residues

Though cellulosic ethanol production has not yet been commercialized, it will be shortly since a number of pilot plants already exist in the country. The reason for this is that second generation technologies have high initial investment costs and higher end-product costs as compared to fossil fuels and first generation fossil fuels. However, this study covers cellulosic ethanol fuels since they represent the rising renewable energy technologies. The United States and Canada are the most advanced countries in cellulosic ethanol, with some thirty next generation companies researching and developing different technologies and feedstocks in the US. In 2010, the cellulosic ethanol production capacity will be 10.1 million gallons. The Energy Independence and Security Act (EISA) has established ambitious goals to promote the production of biofuels by 2022, notably 36 billion gallons from cellulosic fuels to compete with corn-based ethanol use (USDA, 2010).

Reports such as those drafted by the Biomass Research and Development Initiative [BRDI] (2008) and US Environmental Protection Agency (2009) stipulate that the EISA mandate could be primarily met by domestic crop residues, forestry biomass and energy crops. Looking at agricultural residues supply, the most harvested crop in the US is corn with 82.32 millions of harvested acres this year (even more than soybean) (FAPRI, 2010). A report also shows the availability of sustainably removable residues from corn in 2005 at 74.8 million dry tons per year (USDA and US.DoE, 2005). The study was conducted in Iowa, which is the highest corn producing state and has been for a number of years with 2.5 million bushels in 2007. Furthermore, a soon-to-be commercial plant with projected production capacity of 25 million gallons per year starting in 2011 is also being implemented in Emmetsburg, Iowa, with agricultural residues as feedstock (USDA, 2010).

Biogas from manure in Germany

In order to show Germany's biogas potential, it was important to show that Germany has a high production rate, the required technologies and infrastructures and plans to develop even further biogas technologies. Biogas production has expanded significantly in Germany in the past years, so much so that the country has become the biggest producer in the world with 2,383.1 ktoe in 2007—some 39% of the European Union's production. There are three main types of biogas sources: landfill gas, sewage sludge gas and other biogases. The main sources in Germany are from other biogases, which are mainly agricultural biogas units but also include decentralized agricultural plants, municipal solid waste methanization plants and centralized co-digestion plants. Agricultural based biogas come from the methanization of liquid manure, agricultural waste and energy crops in small biogas units on farm or co-digestion units. The most used energy crops are maize, wheat and sunflower. However, in Germany, the most widely-used cereal is maize (EurObserv'ER, 2008). Germany also implemented the world's largest biogas plant in the city of Konnern in 2009, consuming 120 000 tons of agricultural raw materials (Burgermeister, 2008). Germany is a technology leader in the biogas sector and, according to the German Biogas Association (GBA), by 2020, biogas will account for 17% of the national grid mix. A study shows that, by 2030, Germany will be the only country able to feed 100GWh of biogas to the gas network (Kram, 2007). Finally, in terms of feedstock supply, Germany has the second largest manure production of EU27 countries with 232 10^6 tons/year, right after France (FAO, 2003).

Biodiesel from tallow in United States

The United States has an expected production capacity for next generation biofuels of 88 million gallons per year by the end of this year, with 75 million gallons coming from one plant in Geismar, Louisiana. This plant is the first renewable synthetic plant in the country and will greatly help in attaining the energy independence goals of the US. The Dynamic Fuels company is still in the implementation phase, mainly producing biodiesel from animal fats, greases and vegetable oils. This feedstock has a great potential for biodiesel production since animal fats are derived from meat processing facilities and their collection and distribution is already established. There are many commercial biodiesel facilities that use animal fat as feedstock, namely the Future Fuel Corporation facility in Batesville, which has an annual production capacity of 59MGY. According to the 1995-2000 USDA averages, total animal fat production in the US was almost 12 billion pounds. This is a substantial amount, especially considering that a fraction of the feedstock would also come from vegetable oil production, which produces 23 billion pounds (Minnesota Department of Agriculture [MDA], 2002). Finally, animal and recycled fats cost significantly less than the most popular feedstocks used for biodiesel production, making them a very attractive alternative to rapeseed and soybean.

Biogas from OFMSW in Italy

In 2007, Italy’s biogas production was the third highest in Europe, with approximately 88% coming only from land fill gases. With this resource, the biogas is directly collected from the landfill centers. The most common waste management practice in Italy is landfilling, and biogas production resources are therefore highly available (EurObserv’ER, 2008). Many studies have been carried out on biogas production from landfills in Italy and show that many landfill sites have been adapted for biogas production. In fact Aronica et al. (2009) calculated the biogas emissions from the Bellolampo landfill in Palermo and concluded that, at this particular site, the amount of biogas is sufficient to make it a single point source with a production of 7 519.97 to 10 153.7 m^3/h. This feedstock rate could provide approximately 75 MWe—enough to power a micro gas turbine.

Syngas from forest residues in Germany

Wood is often used as feedstock for gasification, producing syngas. Regions with good potential for syngas production, in this case, must show high forest residue resources. The main woody biomass comes from thinning operations and final felling, which are considered to be untapped resources that could be exploited for energy purposes. After Sweden, Germany shows the largest potential in the EU, with approximately 320 PJ/year (Ericsson, K., Nilsson L., 2005). Another interesting fact is that Germany has older forests that can ensure high cutting rates for a number of years without affecting the production functions of the forest (United Nations Economic Commission for Europe [UNECE], FAO Timber Section, 2008). Additionally, there is a build-up phenomenon happening in Northern Europe from an in-balance between the growth rate (forest area and productivity) and harvesting in the managed forests, with harvesting figures remaining significantly lower than those for growth. Of the total annual forest increments of Eastern and Western Europe, Scandinavia, the Mediterranean and NW Russia totalling 880 Mm3, only about 420 Mm3 is currently being harvested commercially. Therefore, a significant share of the remainder (460Mm3) may be available for sustainable bioenergy production.

Europe produces 13 763 MWth of syngas capacity—the second largest in the world. Germany has, by far, the most gasification plants, with a total of twenty one operating plants, five of which use biomass and waste as feedstock ([NETL] 2007). Furthermore, the Federal Ministry of Economics and Labor in Germany initiated a R&D program known as COORETEC (CO_2 reduction technologies) that has led to a wide range of gasification research projects with the goal of building zero-emission power plants.

3- Coal

Syngas from China

China's alternative fuel potential will be defined in a different way than biofuels since coal is already extracted and used in massive amounts. Therefore, the only validations needed are a steady supply of coal for the next decades and continued production. China's coal industry is the world's largest, producing 28 million tons of coal in 2008, and accounts for 81 % of the national grid mix according to the IEA (2007). A projection from IEA (2006) and Beauregard-Tellier (2007*)* states that coal fired power plants are expected to dominate the market, producing up to 6 000 TWh in 2030 and ensuring the country's continued coal production. Other experts agree, concluding that coal fired plants will continue to dominate the Chinese electricity sector for decades to come (IEA, 2006). China's steady supply of coal comes from its abundant resource—an estimated 114 billion metric tons. In fact, China possesses the third largest coal reserves in the world after the US and Russia (British Petroleum [BP], 2006).

As previously stated, only liquid and gaseous fuels may be used in the small gas turbines studied as part of this project. The coal produced in China is therefore considered feedstock for the production of the alternative fuel analyzed in the syngas from China scenario. In order to obtain syngas, the feedstock must be processed through coal gasification. Another important factor in considering China was the country's highly developed technology for syngas production. Furthermore, China also actively cooperates with foreign CGT holders and introduced several advanced CGT technologies, including the Texaco coal-water slurry technology, Shell Dry Coal Dust Gasification Technique and GSP Dry Coal Dust Gasification Technique (United Nations Educational, Scientific and Cultural Organization [UNESCO], SHELL Company, 2007). The Asia/Australia region has the biggest share (34%) of the world's gasification capacity. China alone has 44 operating plants converting coal into a variety of chemicals (National Energy Technology Laboratory [NETL], 2007).

Syngas from coal in the United States

As previously stated, with 2118 TWh, the United States is the second biggest coal consumer for electricity generation purposes after China, (IEA, 2009). An OECD and IEA (2010) projection affirmed that there will be a substantial increase in coal-fired power plants in the US, with approximately 26% growth in electricity production as compared to 2007. This would increase consumption to about 27 quadrillion Btu in North America by 2030, making the US the region with by far the highest consumption rate as compared to Asia and Europe. Also, the US has the biggest coal reserves in the world with 273 billion tons, Russia and China following with 173 and 126 billion tons, respectively (Hutchison, 2009). The United States has a 14% share of the world's syngas capacity almost all to itself, with twenty operating gasification plants (seven are coal or petroleum fed and one is the only plant in the world able to produce pipeline quality gas) (NETL, 2007). This clearly shows the United States' technological advantage in coal gasification.